



# Accelerator facility in the FAIR Project

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*FAIR Scientific Director (des.)*

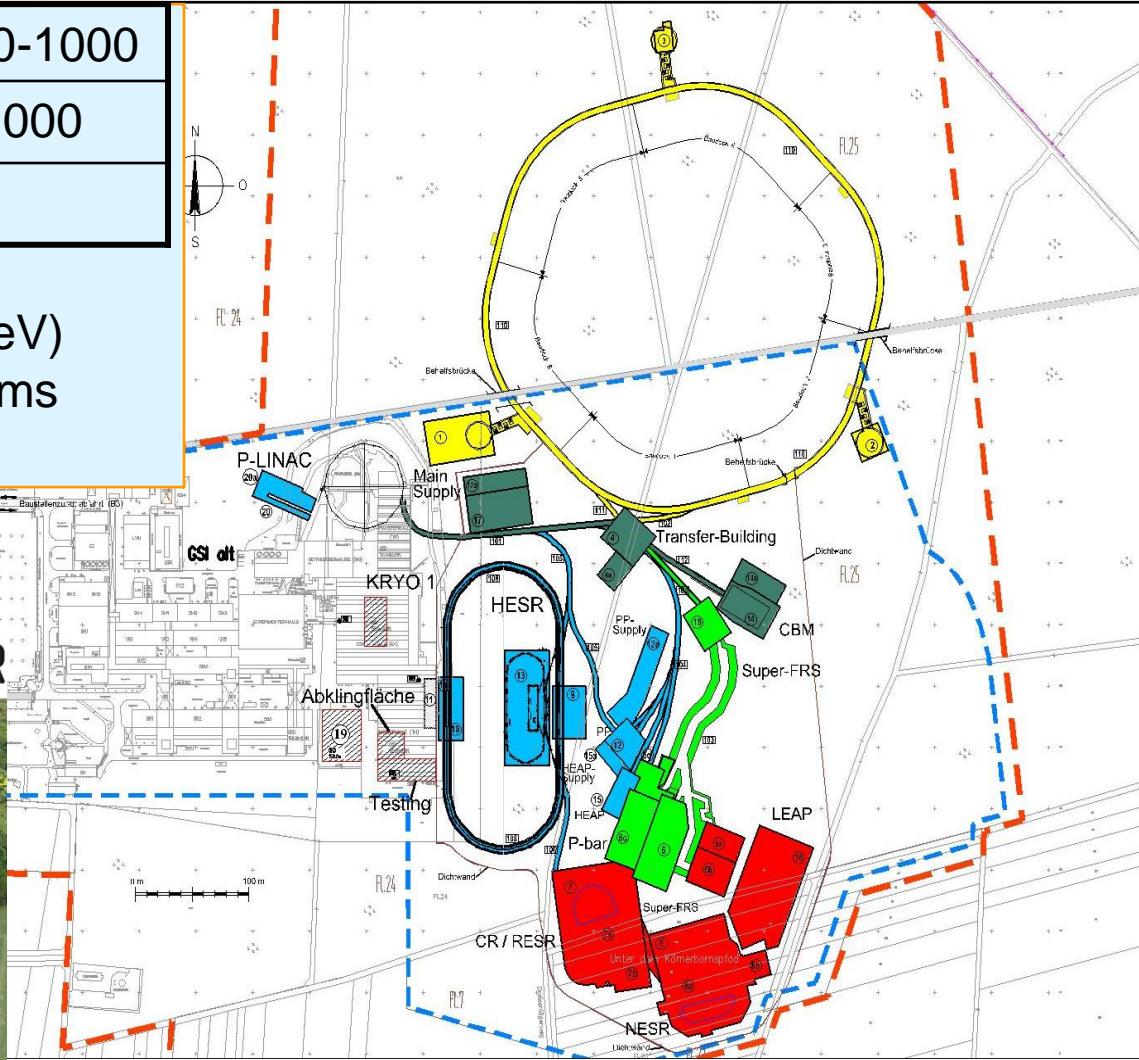
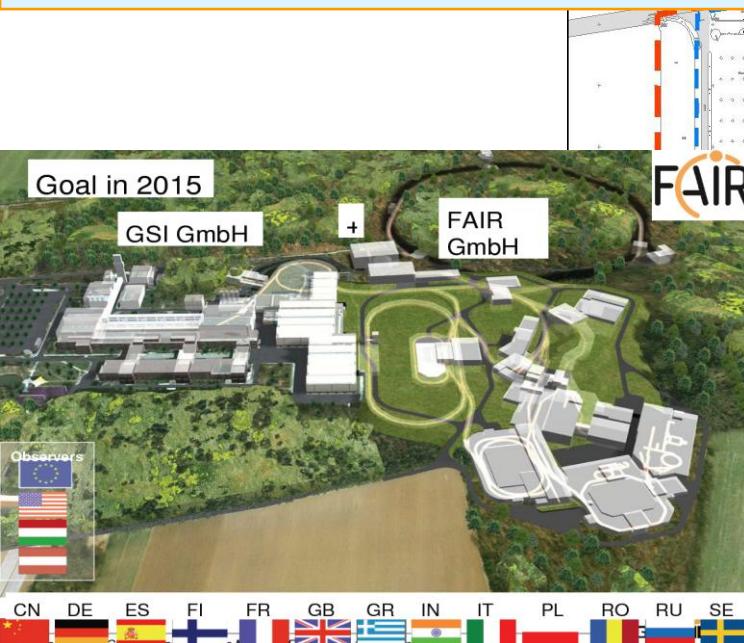
@ Uni Frankfurt 29.01.2010



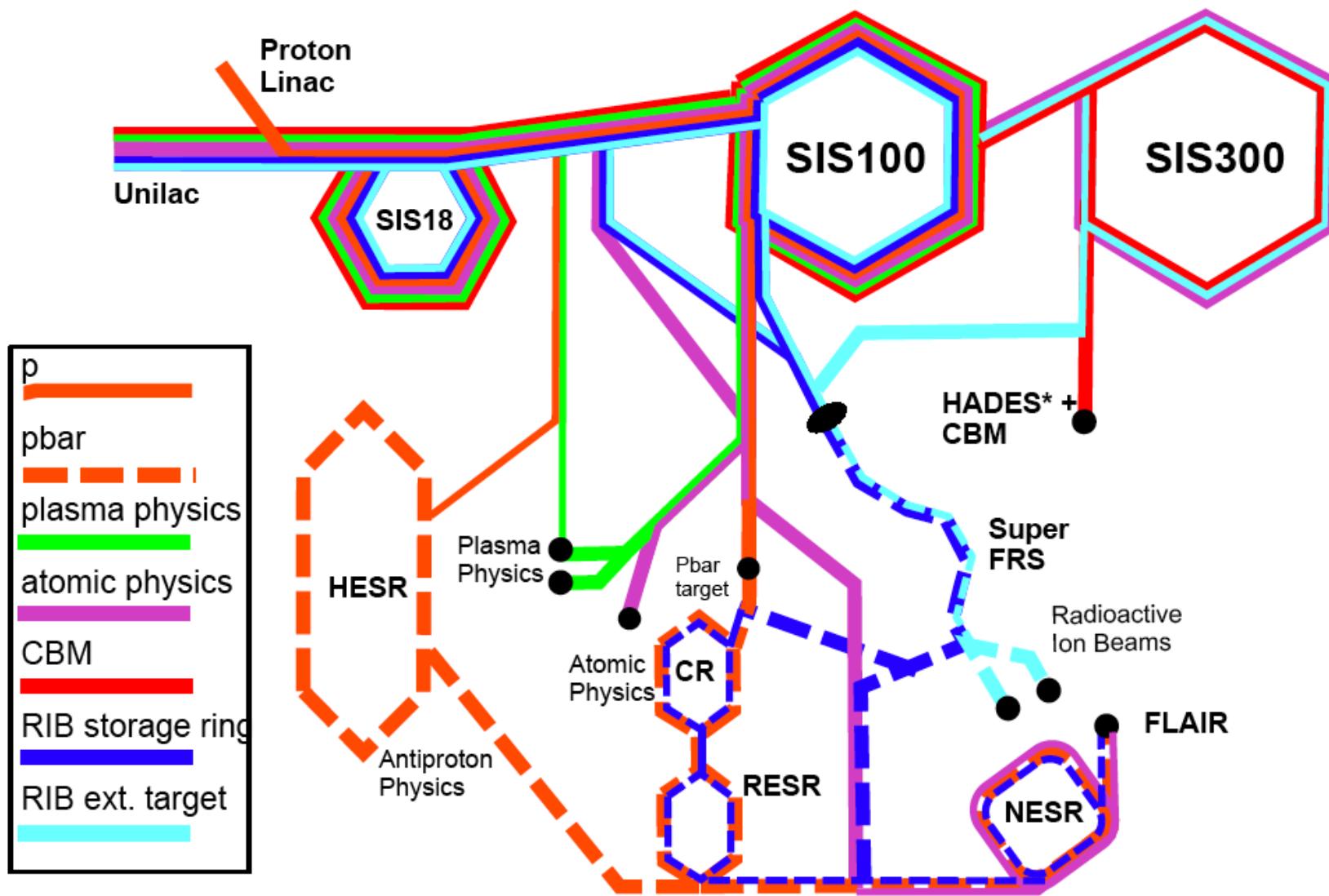
# GSI/FAIR Accelerator Facility

Primary Beam Intensity	x 100-1000
Secondary Beam Intensity	x 10 000
Heavy Ion Beam Energy	x 30

- New: Cooled pbar Beams (15 GeV)
- Intense Cooled Radioactive Beams
- Parallel Operation



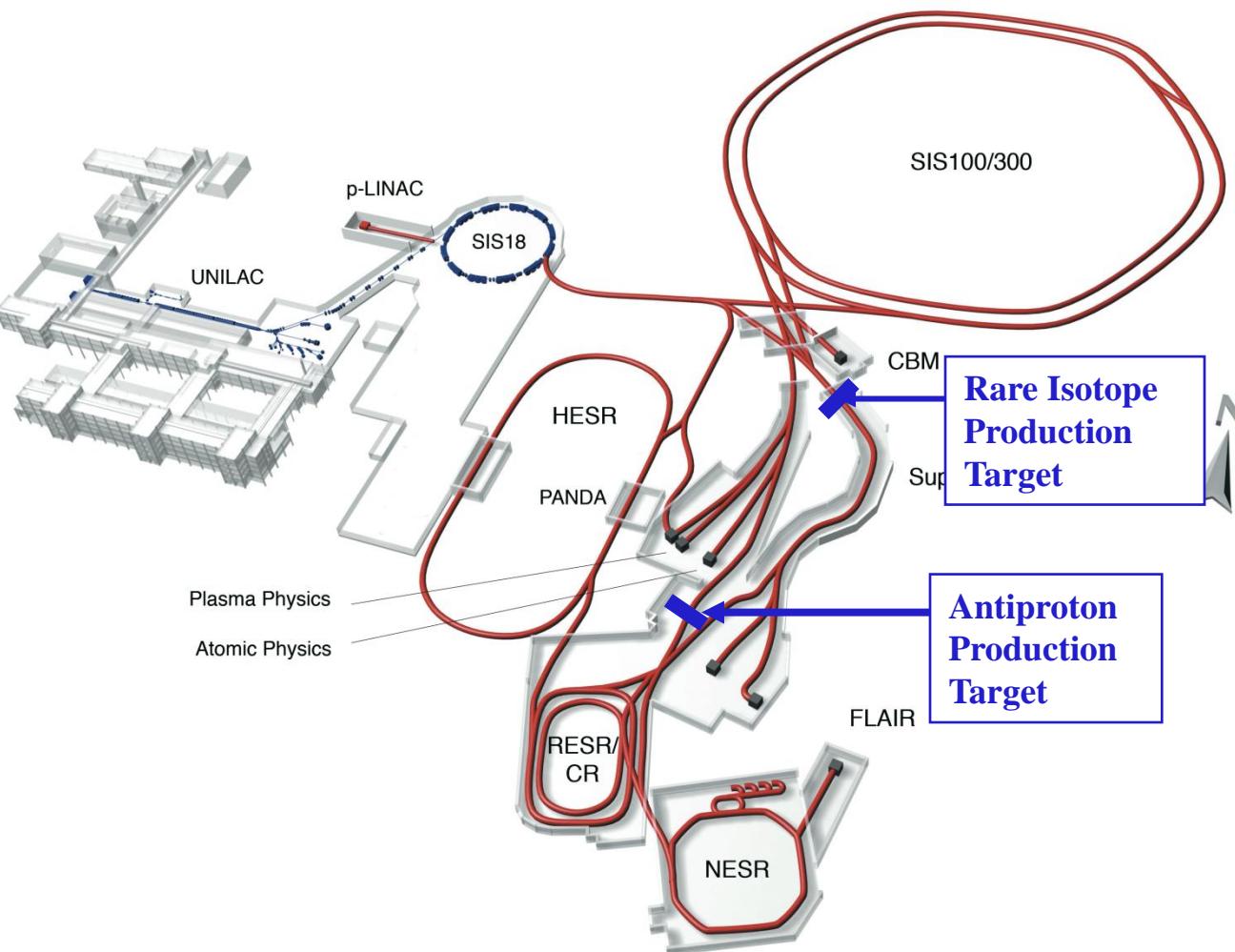
# *Up to 4 fold Parallel Operation at FAIR !*



# International FAIR Project: *the Intensity Frontier*

## Key Technologies

- Beam cooling
- Rapidly cycling superconducting magnets



## Primary Beams

- All elements up to Uranium
- Factor 100-**1000** over present intensity
- **50ns bunching**

## Secondary Beams

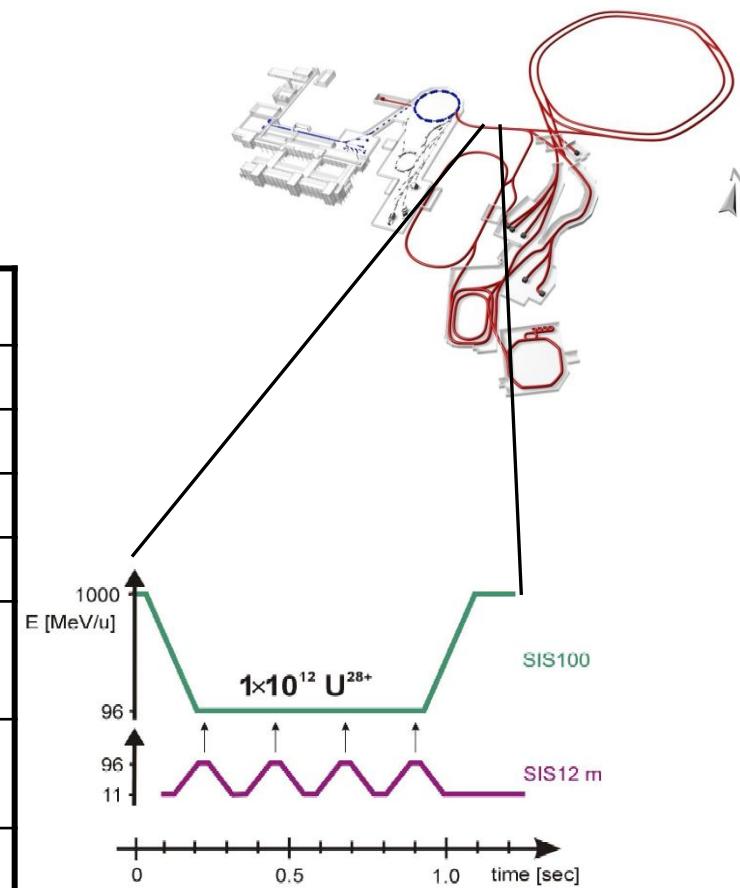
- Rare isotope beams up to a factor **of 10 000** in intensity over present
- Low and high energy **antiprotons**

## Storage and Cooler Rings

- Rare isotope beams
- $e^-$  – Rare Isotope collider
- **$10^{11}$**  stored and cooled antiprotons for **Antimatter** creation

SIS18	Protons	Uranium
Number of ions per cycle	$5 \times 10^{12}$	$1.5 \times 10^{11}$
Initial beam energy	70 MeV	11 MeV/u
Ramp rate	10 T/s	10 T/s
Final beam energy	4.5 GeV	200 MeV/u
Repetition frequency	2.7 Hz	2.7 Hz

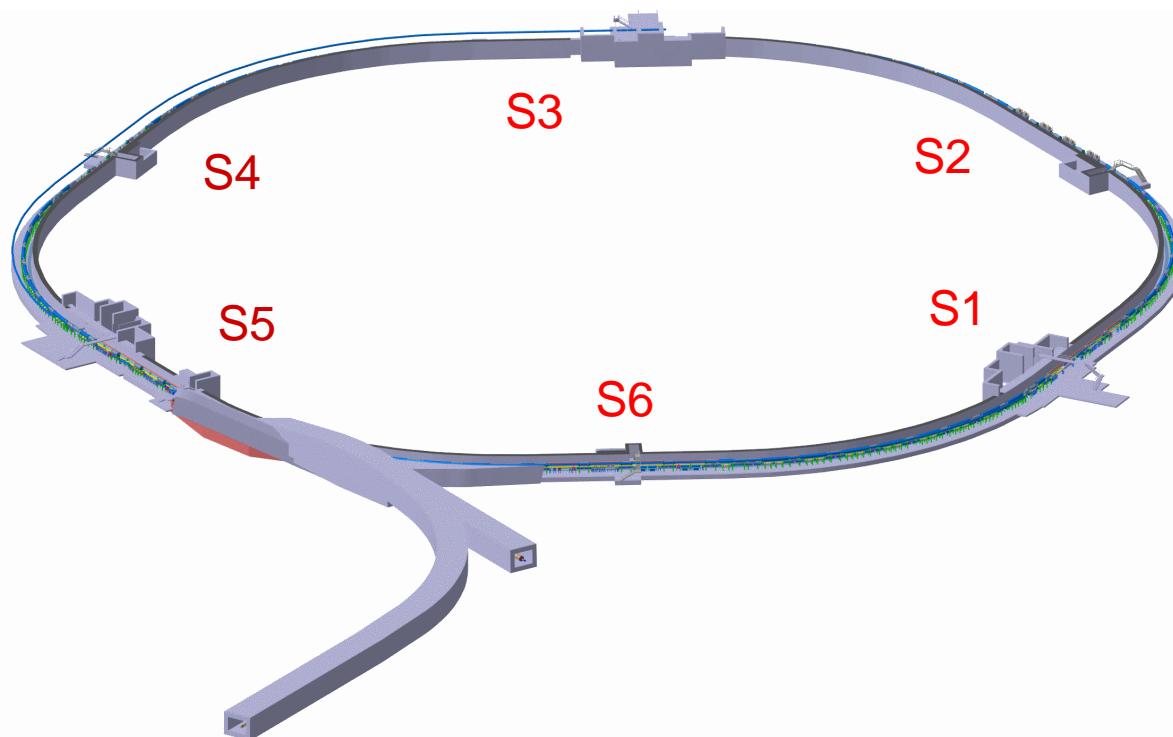
SIS100	Protons	Uranium
Number of injections	4	4
Number of ions per cycle	$2.5 \times 10^{13}$ ppp	$5 \times 10^{11}$
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz



# Technical Subsystems

## Sixfold Symmetry

- Sufficiently long and number of straight sections
- Reasonable line density in resonance diagram
- Good geometrical matching to the overall topology

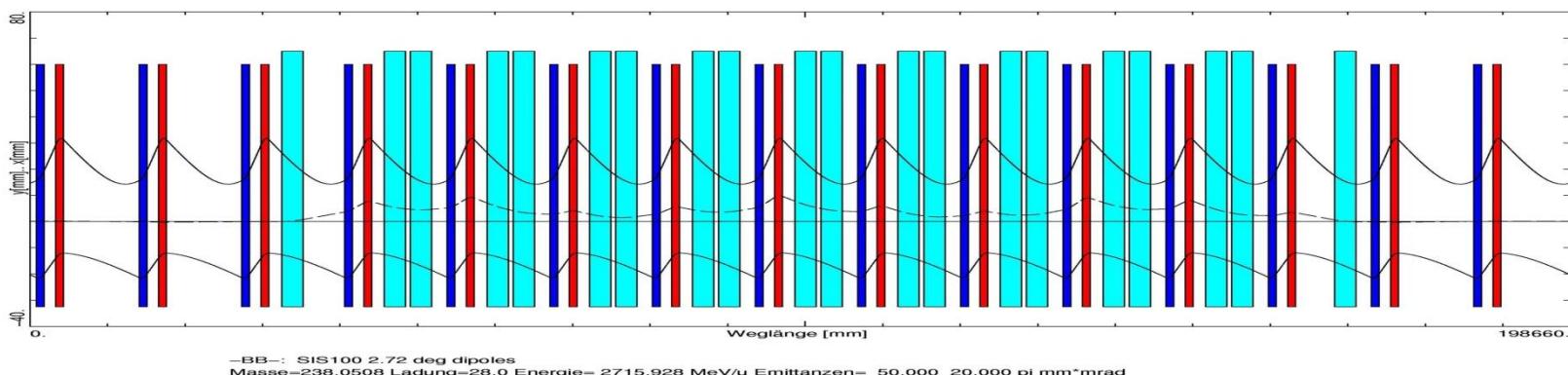


- S1:** Transfer to SIS300
- S2:** Rf Compression  
(MA loaded)
- S3:** Rf Acceleration  
(Ferrite loaded)
- S4:** Rf Acceleration  
(Ferrite loaded)
- S5:** Extraction Systems  
(slow and fast)
- S6:** Injection System plus  
RF Acceleration and  
Barrier Bucket

The SIS100 technical subsystems define the length of the straight sections of both synchrotrons

# SIS100 Lattice Characteristics

- Maximum transverse acceptance (minimum 3x emittance at injection) at limited magnet apertures (problems: pulse power, AC loss etc.)
- Vanishing dispersion in the straight sections for high dp/p during compression
- Low dispersion in the arcs for high dp/p during compression
- Sufficient dispersion in the straight section for slow extraction with Hardt condition
- **Shiftable transition energy (three quadrupole power busses) for p operation**
- Sufficient space for all components and efficient use of space
- Enabling slow, fast and emergency extraction and transfer within one straight.
- Peaked distribution and highly efficient collimation system for ionization beam loss

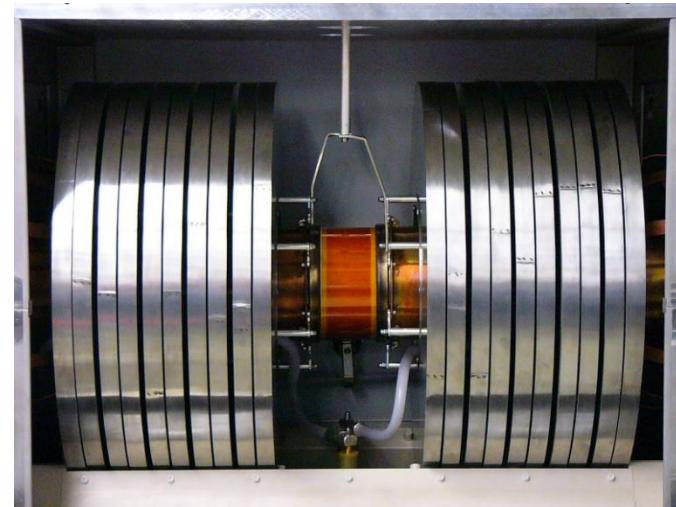


# SIS100 Radiofrequency: Overview

	FBTR	f [MHz]	#	Technical Concept
Acceleration System	$h=10$ 400 kV	1.1–2.7	20 (SIS100) 8 (SIS300)	Ferrit ring core, "narrow" band cavities
Compression System	$h=2$ 640 kV	0.395- 0.485	16	Magnetic alloy ring core, broad band (low duty cycle) cavities
Barrier Bucket System	15kV	2	2	Magnetic alloy ring core, broad band (low duty cycle) cavities



SIS18 ferrit loaded accel. cavity



SIS18 MA loaded bunch compression cavity

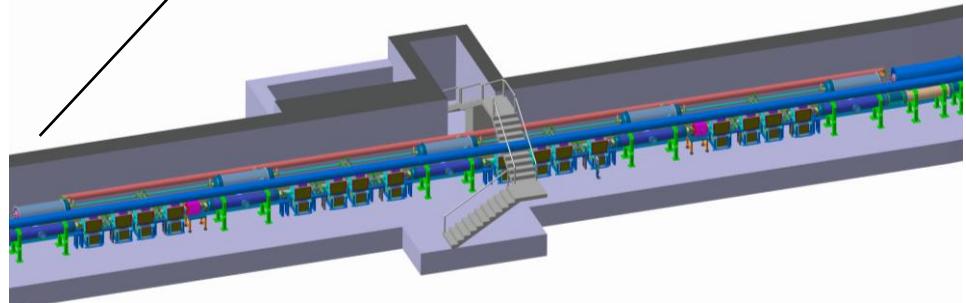
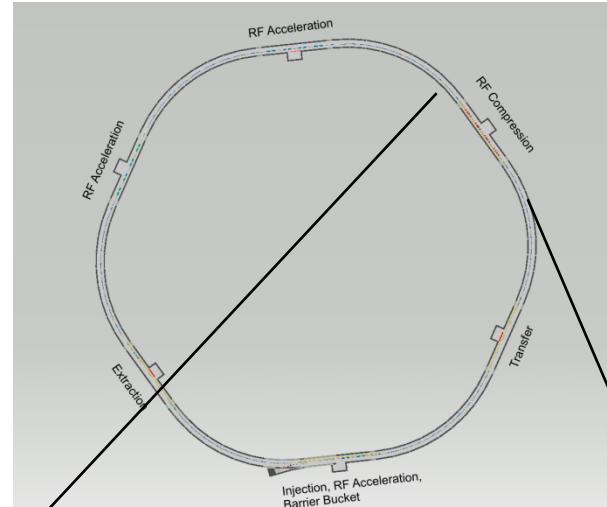
# Bunch Compression Systems



Short pulse ( $500 \mu\text{s}$ ), high power bunch compressor developed at GSI



World wide MA core material survey

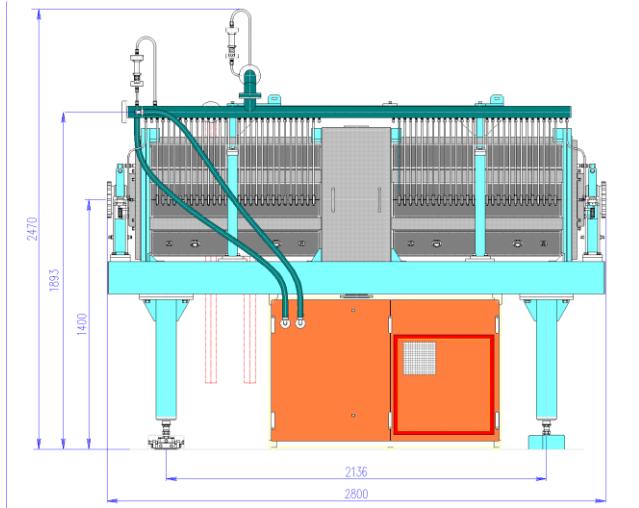


16 MA compression cavities in section S2

# Rf: Acceleration Sections

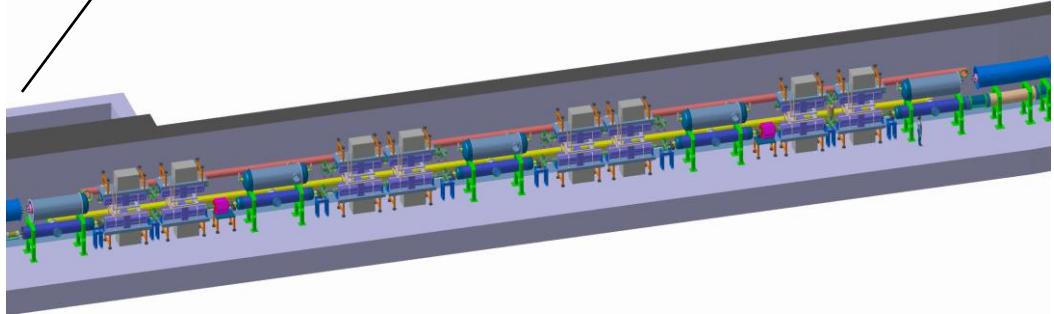
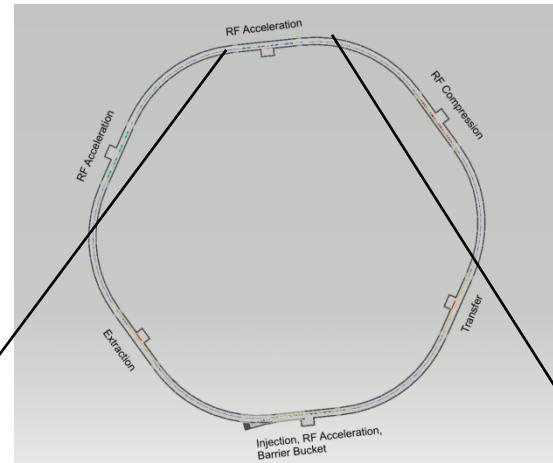
## Acceleration Cavities:

- Design study completed (BINP)



Minimization of shunt impedance:

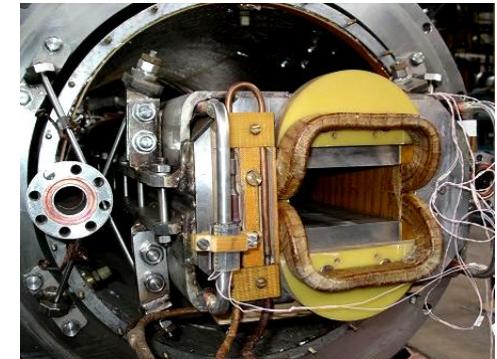
Fast semi-conductor gap switch R&D



# SIS100 Fast Ramped S.C. Magnets

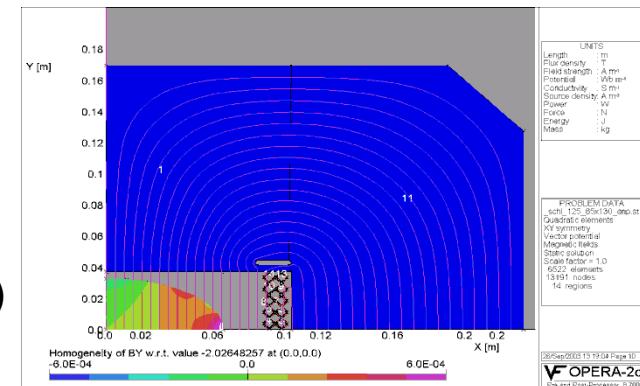
## R&D Goals

- Reduction of eddy / persistent current effects at 4K (3D field, AC loss)
- Improvement of DC/AC-field quality
- Guarantee of long term mechanical stability ( $\geq 2 \cdot 10^8$  cycles )



## Activities

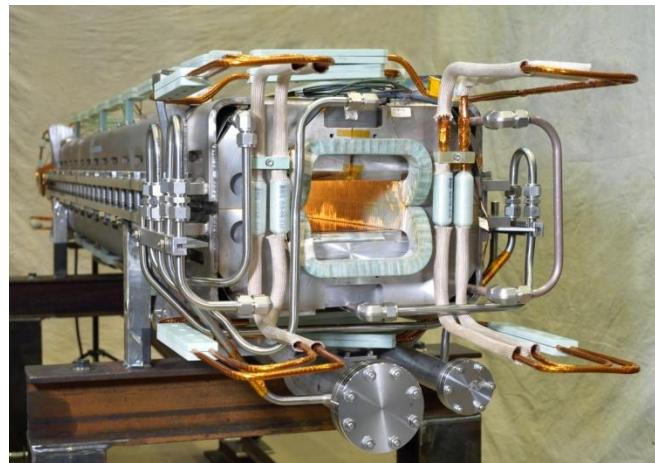
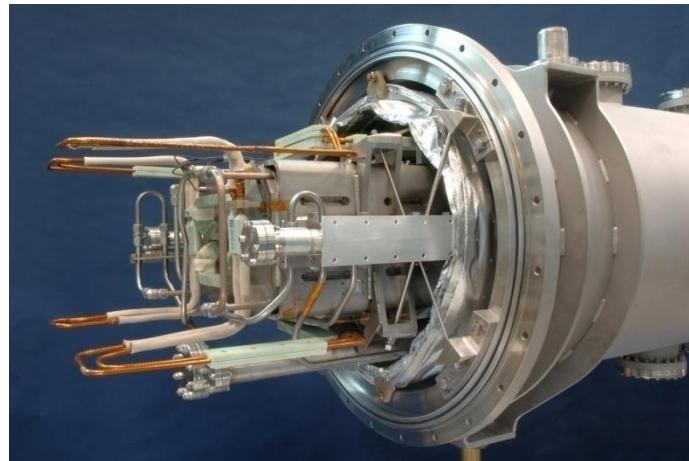
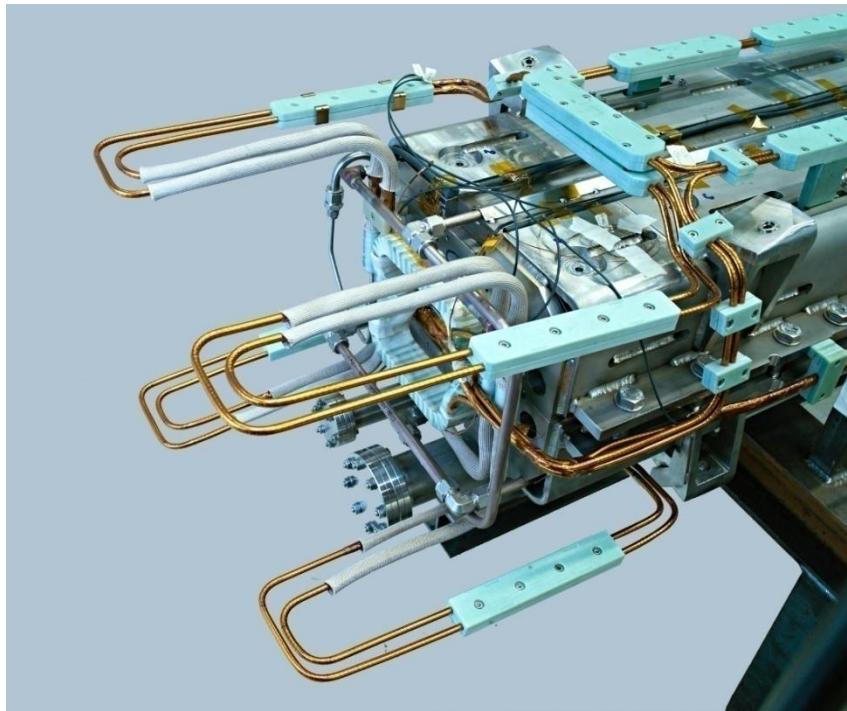
- AC Loss Reduction (exp. tests, FEM)
- 2D/3D Magnetic Field Calculations (OPERA, ANSYS, etc.)
- Mechanical Analysis and Coil Restraint (design, ANSYS) (>Fatigue of the conductor and precise positioning)



Experimental studies with modified Nuklotron magnets in JINR

# Full Length SIS100 Prototype Dipole

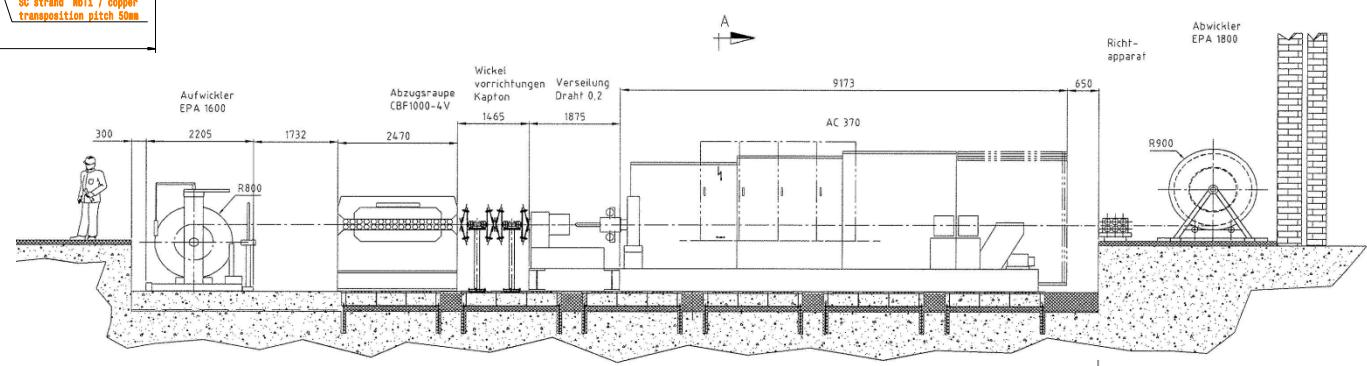
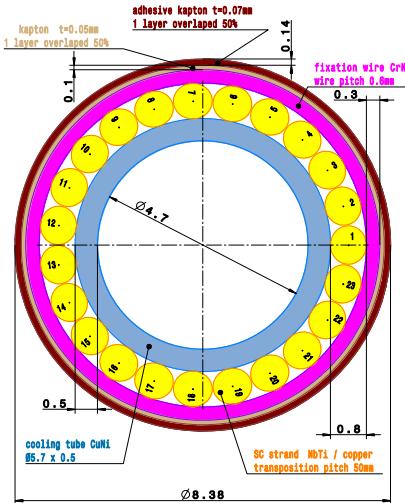
Manufactured by BNG (Würzburg)



- Second straight dipole and quadrupole under manufacturing at JINR
- Curved dipole under manufacturing at BINP

# Nuklotron Cable Production at BNG

Second Nuklotron type cable production capability set-up at BNG in Würzburg



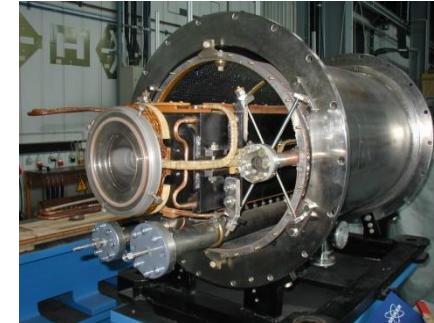
# Two Stage Synchrotron SIS100/300

- 1. High Intensity- and Compressor Stage

SIS100 with fast-ramped superconducting magnets and a strong bunch compression system.

Intermediate charge state ions e.g. U<sup>28+</sup>-ions up to 2.7 GeV/u  
Protons up to 30 GeV

$$B_p = 100 \text{ Tm} - B_{\max} = 1.9 \text{ T} - dB/dt = 4 \text{ T/s (curved)}$$

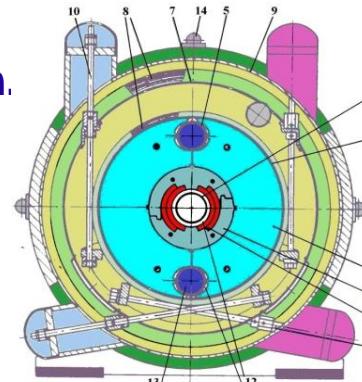


- 2. High Energy- and Stretcher Stage

SIS300 with superconducting high-field magnets and stretcher function.

Highly charged ions e.g. U<sup>92+</sup>-ions up to 34 GeV/u  
Intermediate charge state ions U<sup>28+</sup>- ions at 1.5 to 2.7 GeV/u with 100% duty cycle

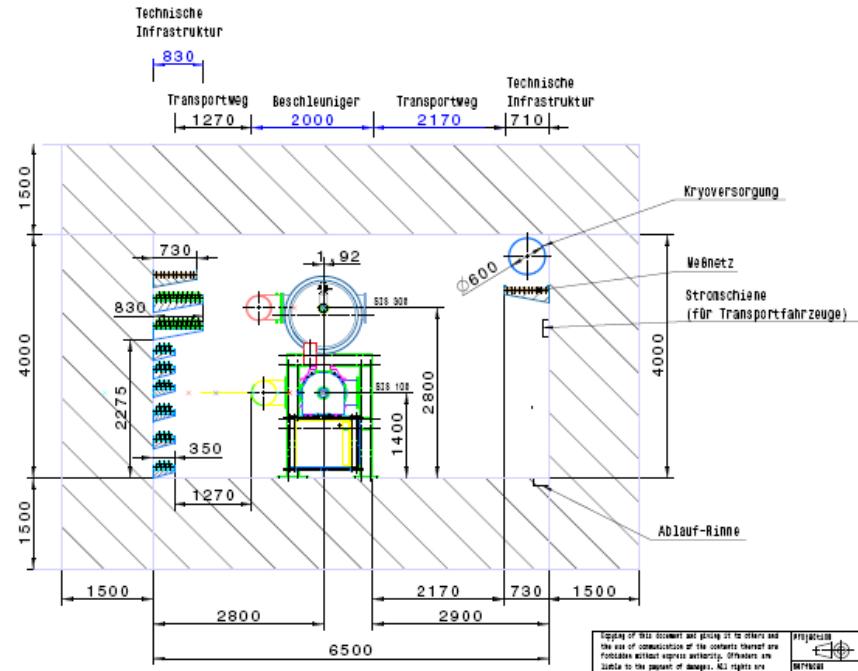
$$B_p = 300 \text{ Tm} - B_{\max} = 4.5 \text{ T} - dB/dt = 1 \text{ T/s (curved)}$$



# System and Ion Optical Design

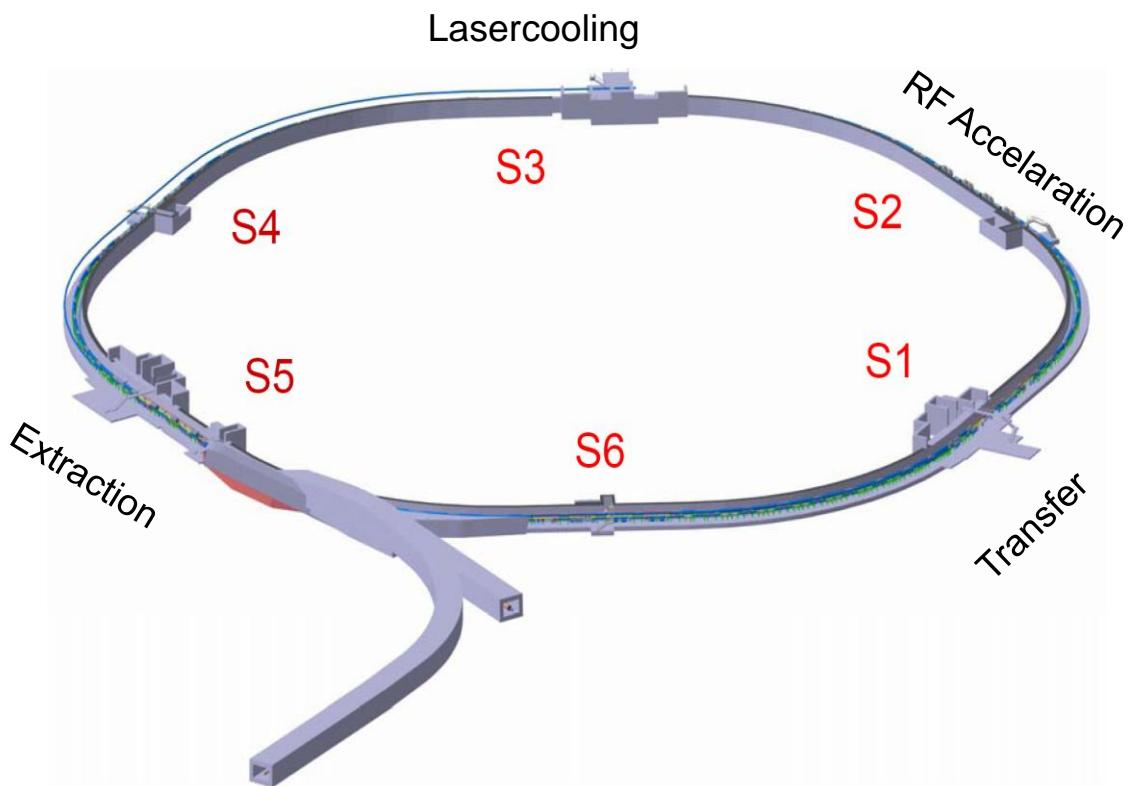
Realisation of two-stage SIS100 and SIS300 concept in one tunnel is challenging:

- Geometrical matching of both synchrotrons with different lattice structures (Doublet and FODO) and different magnet technologies (superferric and cos $\theta$ )
- Ratio between straight section length and arc length with fixed circumference defined by the warm straight section requirements of SIS100
- Fast, slow and emergency extraction in one short straight and precisely at the same position, with the same angle and fixed distance between the SIS100 and SIS300 extraction channel
- Vertical extraction of SIS100 bypassing SIS300 (on top of SIS100)
- Transfer between SIS100 and SIS300, 1.4 m difference, many geometrical constraints



# SIS300 Basic Requirements

- The SIS300 will be installed on top of SIS100 in the same tunnel.
- The maximum magnetic rigidity is 300 Tm in high energy mode
- The magnetic rigidity is up to 100 Tm in stretcher mode
- Bent super conducting  $\cos(\theta)$ -type magnets will be used with a maximum field of 4.5 T in the dipoles.
- The injection into SIS300 is performed via a vertical transfer line from SIS100.
- The design injection energy is 1500 MeV (64 Tm). The expected beam emittance is  $10 \times 4 \pi \text{ mm mrad}$ . Lower injection rigidities are possible with reduced intensity down to 27 Tm in stretcher mode.
- The slow extraction is performed vertically into an extraction beamline parallel to the one of SIS100.
- In case of emergency the beam is dumped into an internal target



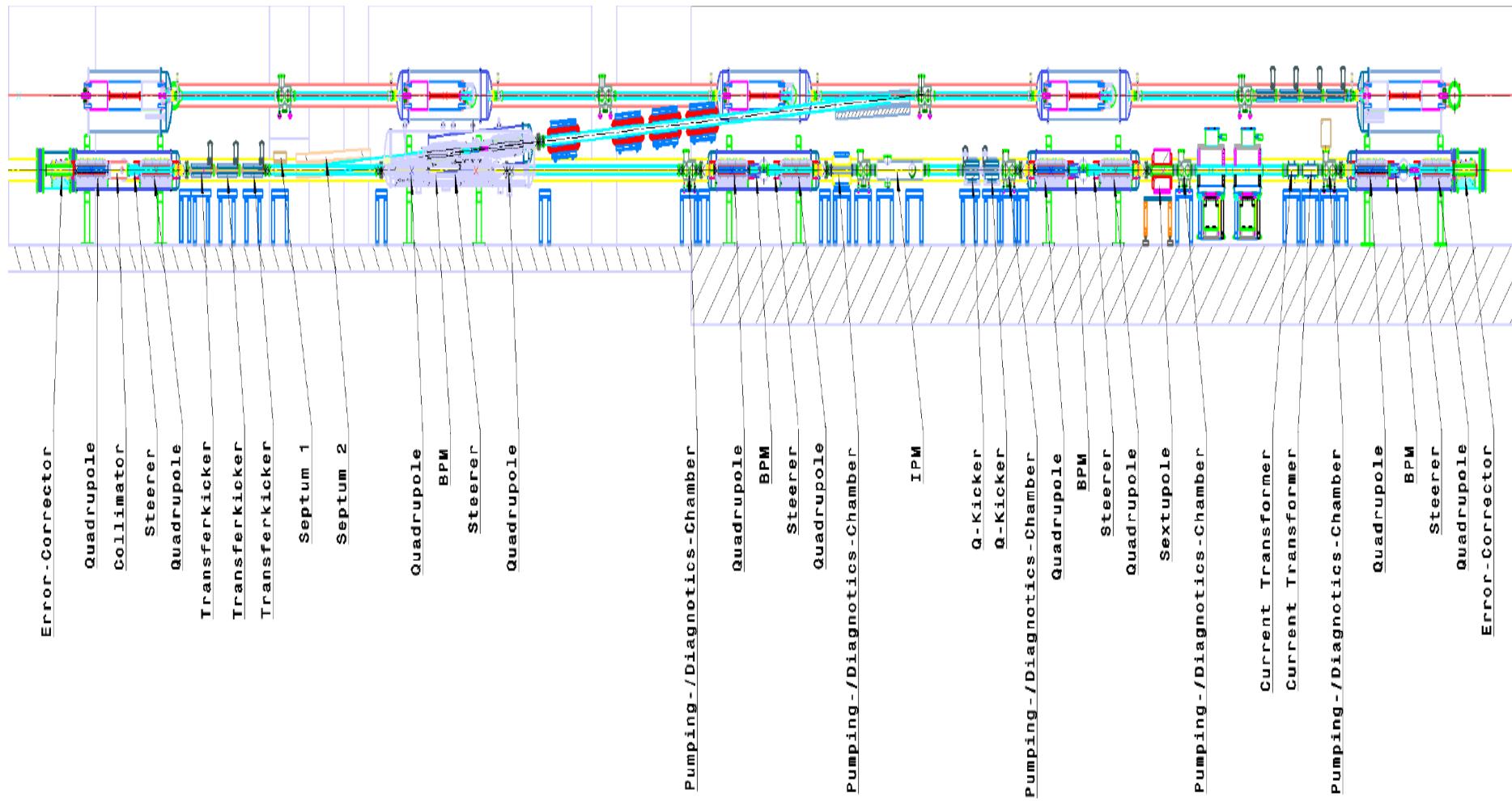
Sixfold symmetry

SIS100 technical subsystems define the length and number of the straight sections of both synchrotrons

Good geometrical matching to the overall geometry

A parallel supply tunnel at the inner shell of the synchrotron

# Transfer Section



# Basic Magnet Parameters

⑩ Flat top up to 100s during extraction

⑩ Dipoles

High energy mode ramped from 1 T to 4.5 T

Stretcher mode static (but ramped to) 0.4 T to 1.5 T

Ramp rate 1 T/s

⑩ Quadrupoles

High energy mode ramped from 10 T/m - 45 T/m

Stretcher mode static (but ramped to) 4 T/m - 15 T/m

Ramp rate 10 T/(ms)

# Main Dipole Parameters

Cos  $\theta$  magnets

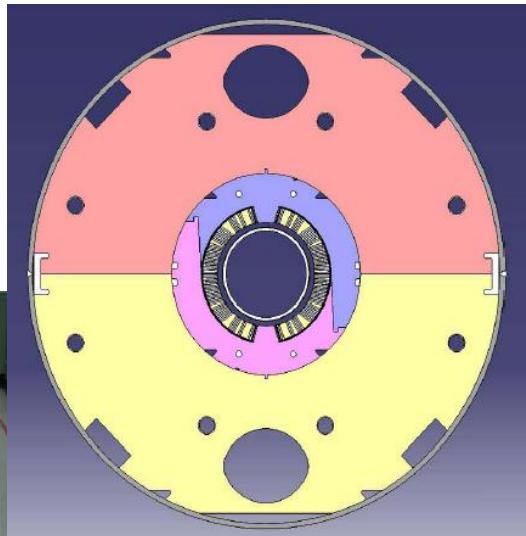
Supercritical He is recooled

	short	long
<b>Maximum magnetic field [T]</b>		<b>4.5</b>
<b>Number of magnets in the ring + reference magnets</b>	<b>12 +1</b>	<b>48 + 1</b>
<b>Magnetic length [mm]</b>	<b>3878.5</b>	<b>7757.0</b>
<b>Bending angle / radius [deg] / [m]</b>	<b>3.333 / 66.67</b>	<b>6.667 / 66.67</b>
<b>Free aperture (beam pipe ID) [mm]</b>		<b>86</b>
<b>Coil inner diameter [mm]</b>		<b>100</b>
<b>Field quality at r=35mm [units]</b>		<b><math>\pm 2</math></b>
<b>Ramp rate [T/s]</b>		<b>1</b>

# Main Dipoles



(courtesy P. Fabbricatore)



(courtesy R. Marabotto)

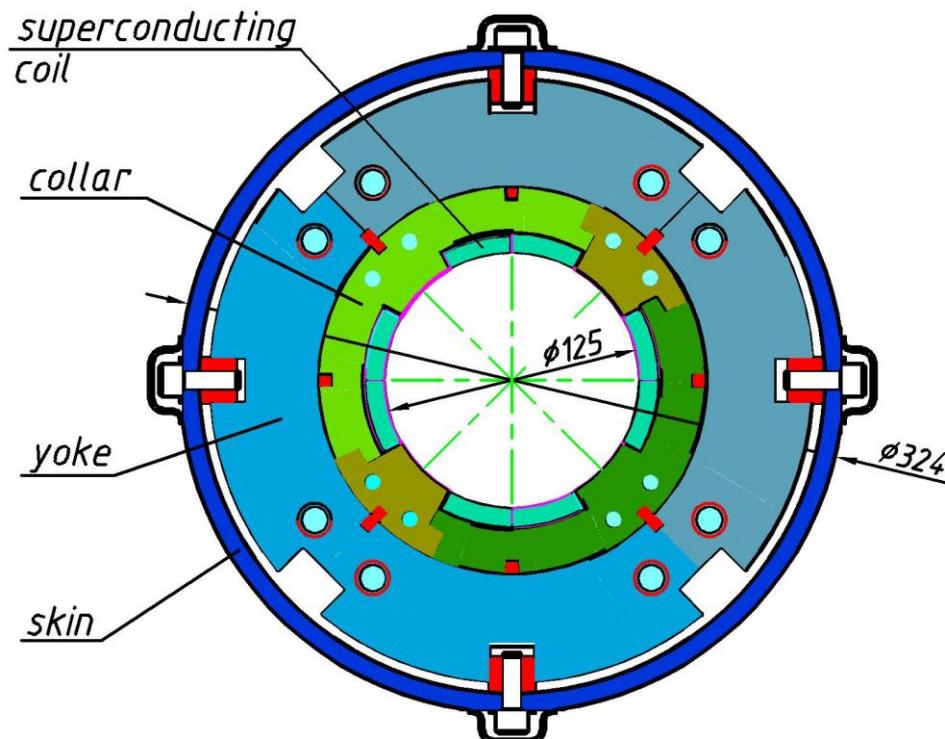
Block number	5
Turn number/quadrant	34 (17+9+4+2+2)
Operating current	8924 A
Yoke inner radius	98 mm
Peak field on conductor (with self field)	4.90 T
Bpeak / Bo	1.09
Working point on load line	69%
Current sharing temperature	5.69 K
Inductance/length	2.9 mH/m
Stored energy/length	116.8 kJ/m

Discorap-Project by INFN  
Magnet finished in 2010

# Main Quadrupoles

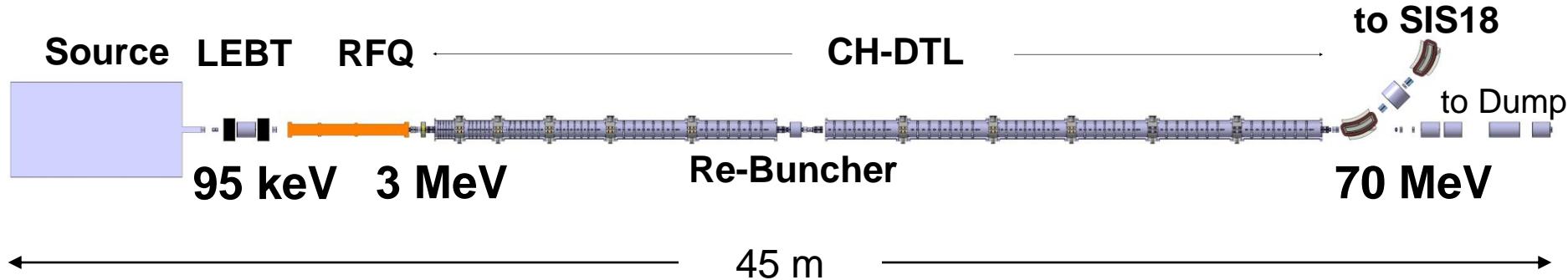
## IHEP Design Study

Block number	3
Turn number/coil	20 (8+7+5)
Strands in cable	19
Strand diameter	0.825 mm
Operating current	6220 A
Yoke inner radius	95 mm
Peak field on conductor (with self field)	3.57 T
Minimum temperature margin	1.6 K
Inductance/length	2.46 mH/m
Stored energy/length	44.4 kJ/m
Ramp-up voltage	3.4 V

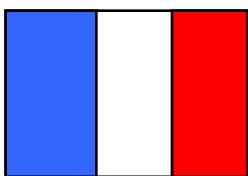


(courtesy L. Tkachenko)  
SIS300  
Precon sortium  
Meeting

## 70 MeV Proton Linac

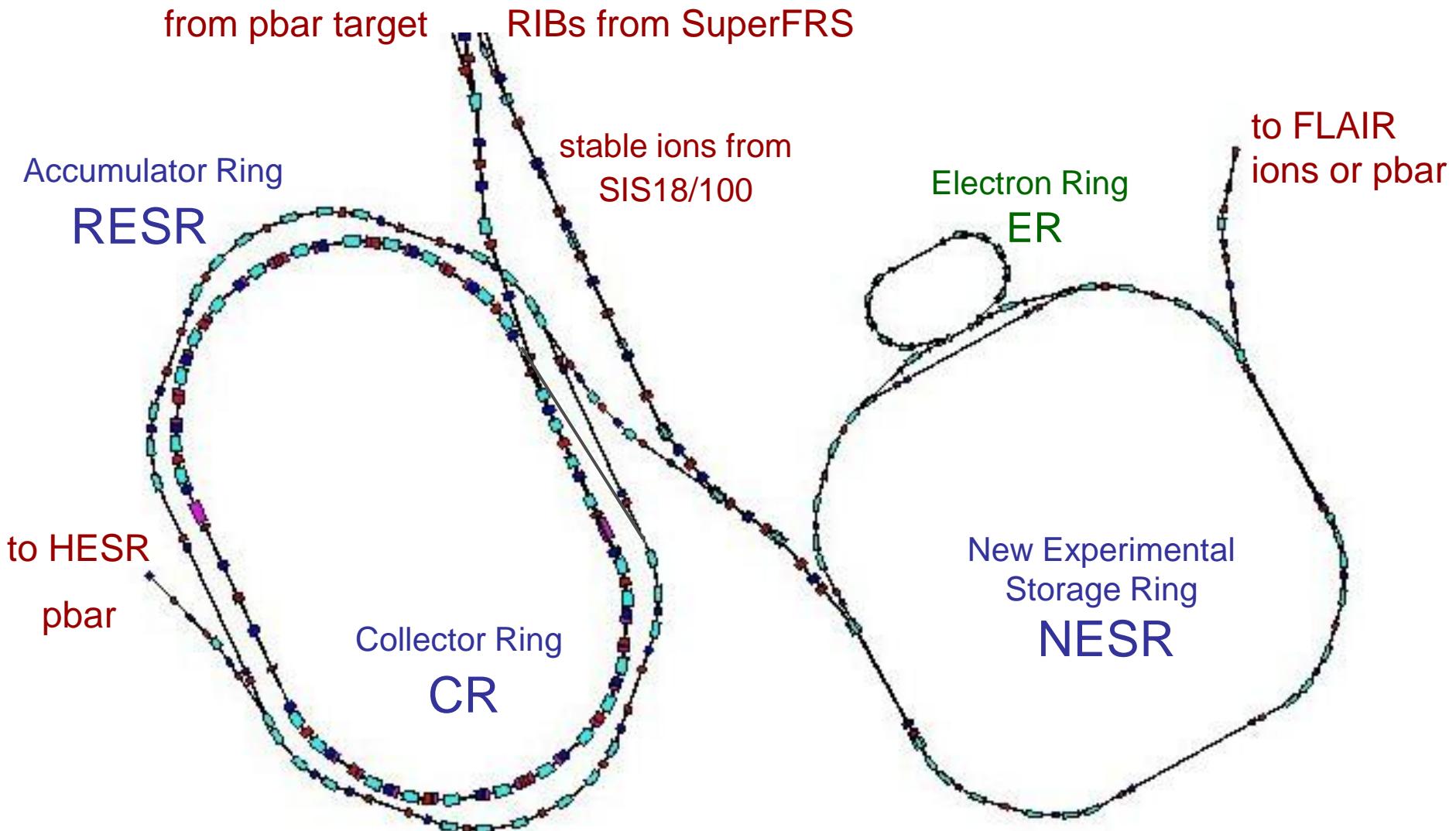


Beam energy	70 MeV
Beam current (op.)	35 mA
<u>Beam current (des.)</u>	<u>70 mA</u>
Beam pulse length	36 $\mu$ s
Repetition rate	4 Hz
Rf-frequency	325.224 MHz
Tot. hor emit (norm.)	2.1 / <u>4.2</u> $\mu$ m
Tot. mom. spread	$\leq \pm 10^{-3}$
Linac length	$\approx 35$ m

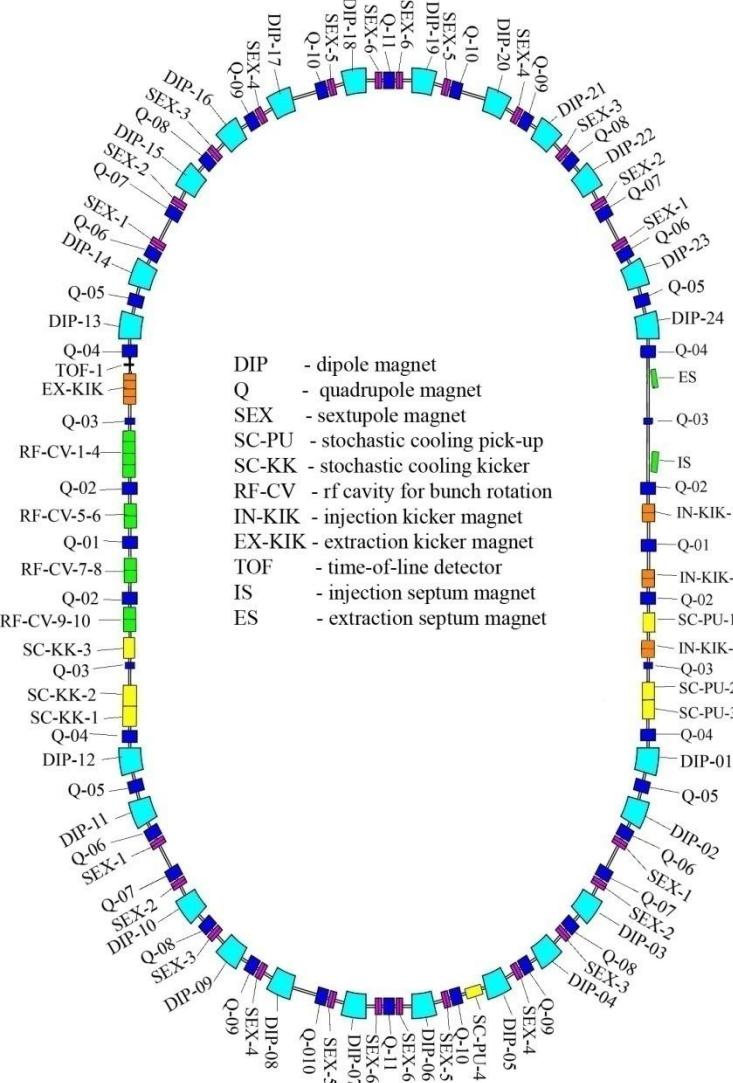


French Participation Total Invest : 1.7 M€

# The FAIR 13 Tm Storage Rings



# The Collector Ring CR



circumference 216 m  
magnetic bending power 13 Tm  
large acceptance  $\varepsilon_{x,y} = 240$  (200) mm mrad  
 $\Delta p/p = \pm 3.0$  (1.5) %

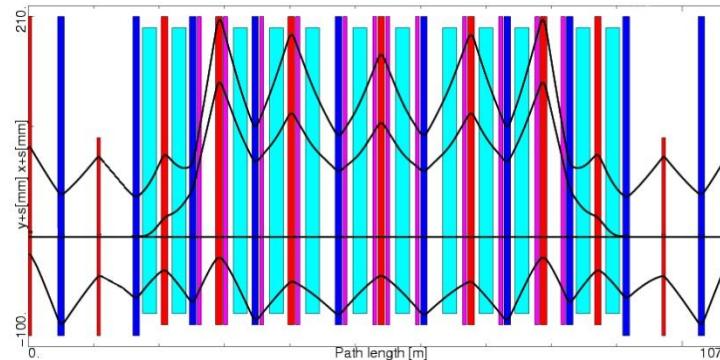
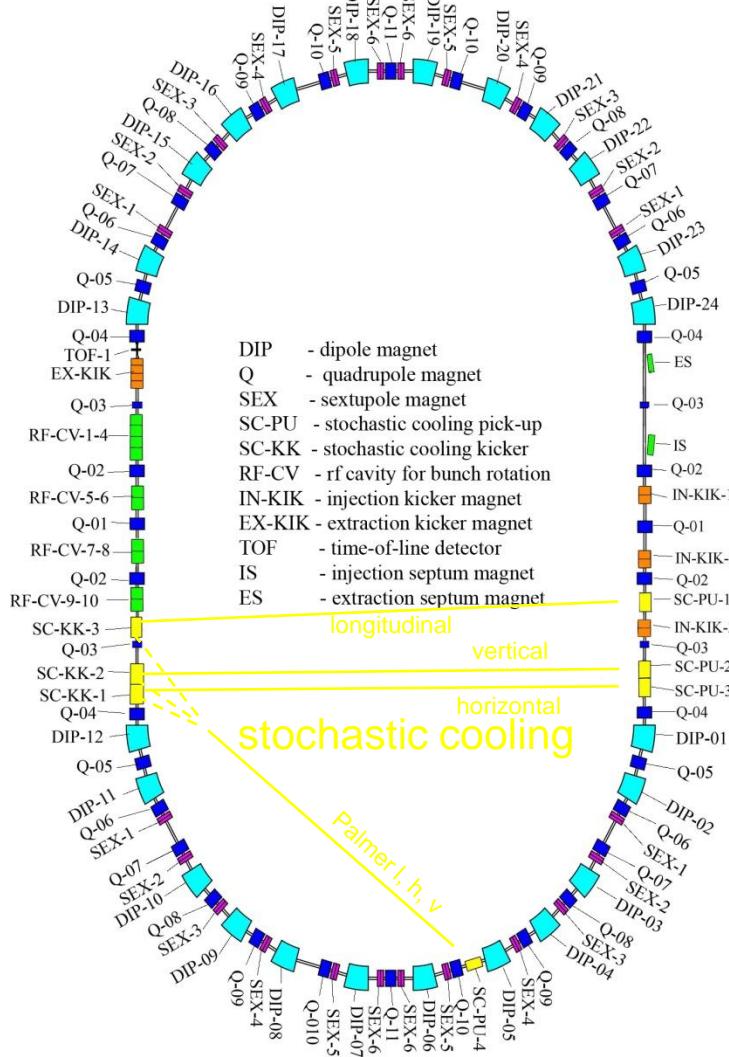
fast stochastic cooling (1-2 GHz)  
of antiprotons (10 s) and  
rare isotope beams (1.5 s)

*fast bunch rotation at  $h=1$   
with rf voltage 200 kV  
adiabatic debunching  
optimized ring lattice (slip factor)  
for proper mixing  
large acceptance magnet system*

additional feature:  
isochronous mass measurements  
of rare isotope beams

option: upgrade of rf system to 400 kV  
and stochastic cooling to 1-4 GHz

# Ion Optical Modes of the CR



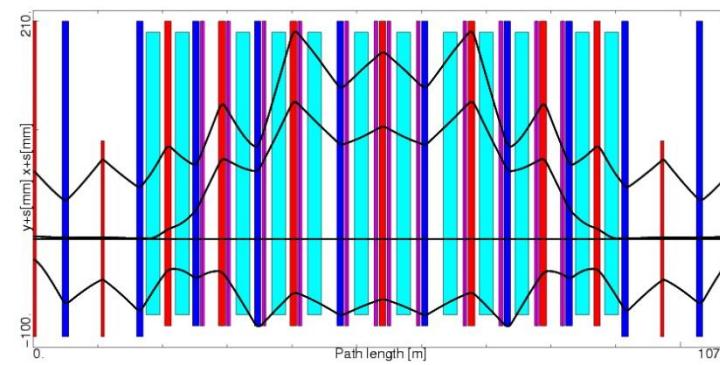
**antiprotons**

$$Q_x = 4.26, Q_y = 4.84$$

$$\gamma_t = 3.7$$

$$\eta = -0.016$$

$$\Delta p/p = 3\%$$



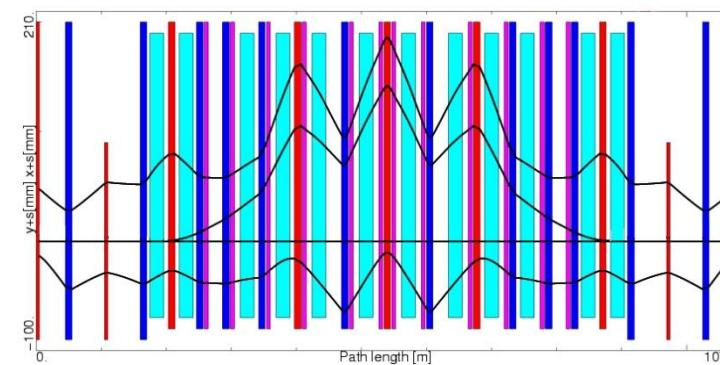
**RIBs**

$$Q_x = 3.21, Q_y = 3.71$$

$$\gamma_t = 2.8$$

$$\eta = +0.185$$

$$\Delta p/p = \pm 1.5\%$$



**isochronous**

$$Q_x = 2.33, Q_y = 4.64$$

$$\gamma_t = 1.67-1.84$$

$$\eta = 0$$

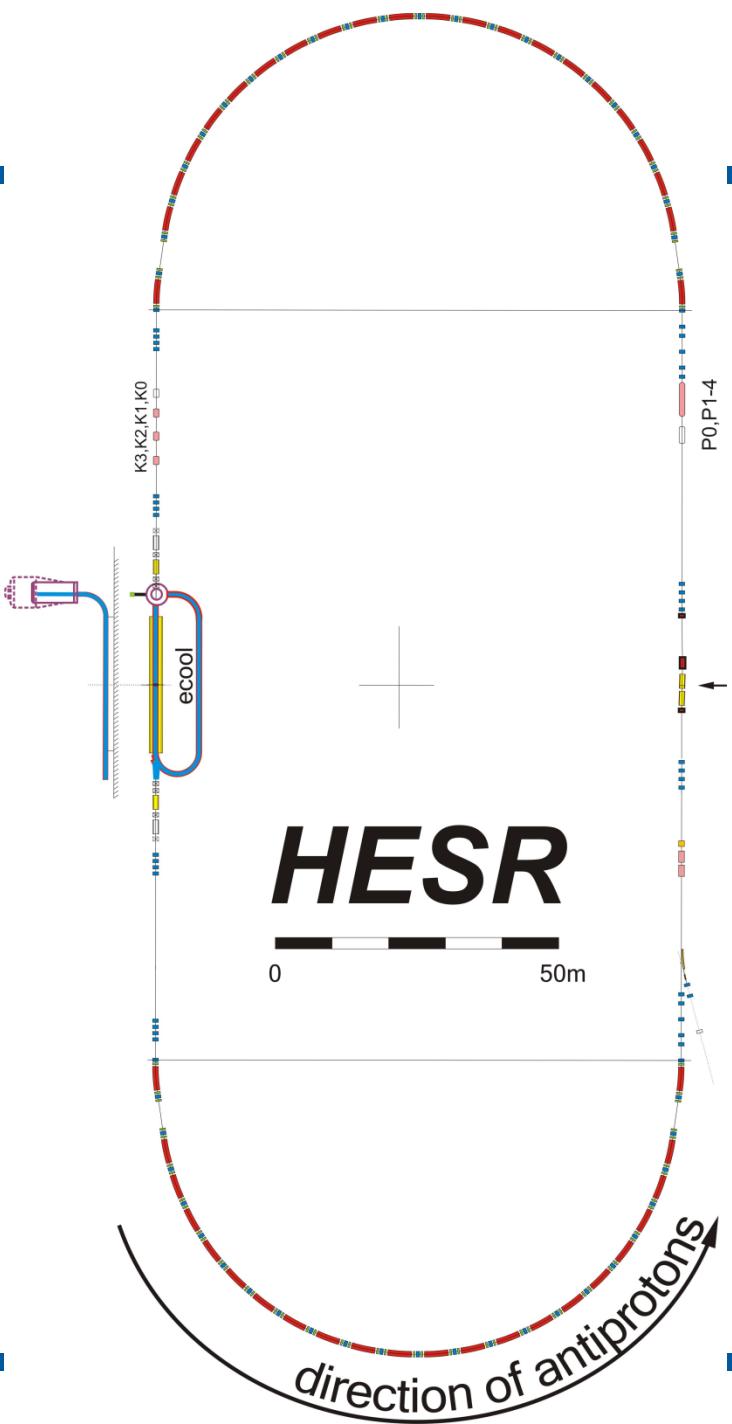
$$\Delta p/p = \pm 0.5\%$$

# Criteria for the Layout of the **HESR**

## ⑩ HESR design driven by the requirements of PANDA:

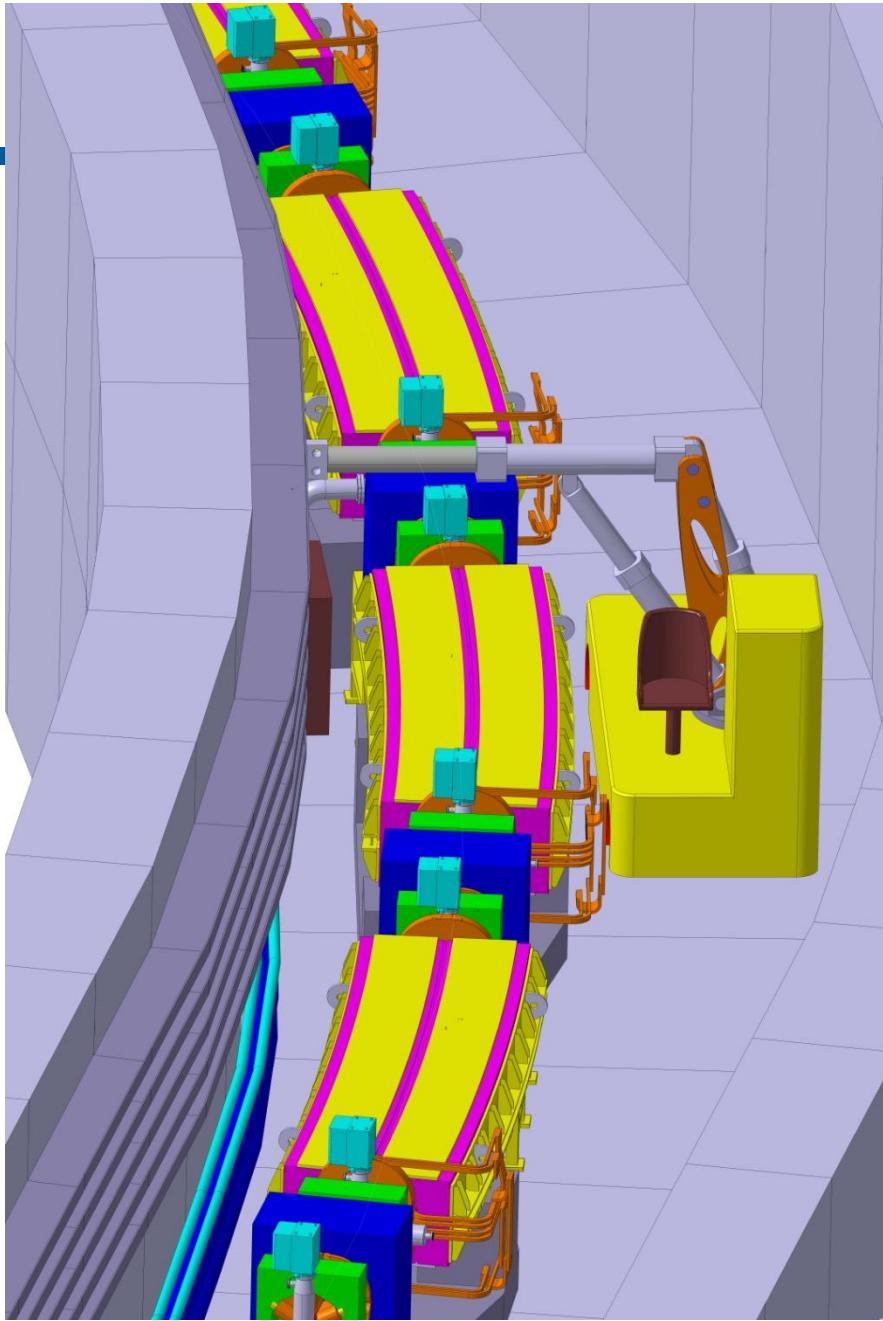
- Antiprotons with  $1.5 \text{ GeV}/c \leq p \leq 15 \text{ GeV}/c$
- High luminosity:
  - Thick targets:  $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - Thick targets:  $4 \cdot 10^{15} \text{ cm}^{-2}$
- High momentum resolution:  $\Delta p/p \leq 4 \cdot 10^{-5}$ 
  - Phase space cooling
- Long beam life time:  $>30 \text{ min}$

# Basic Data of HESR

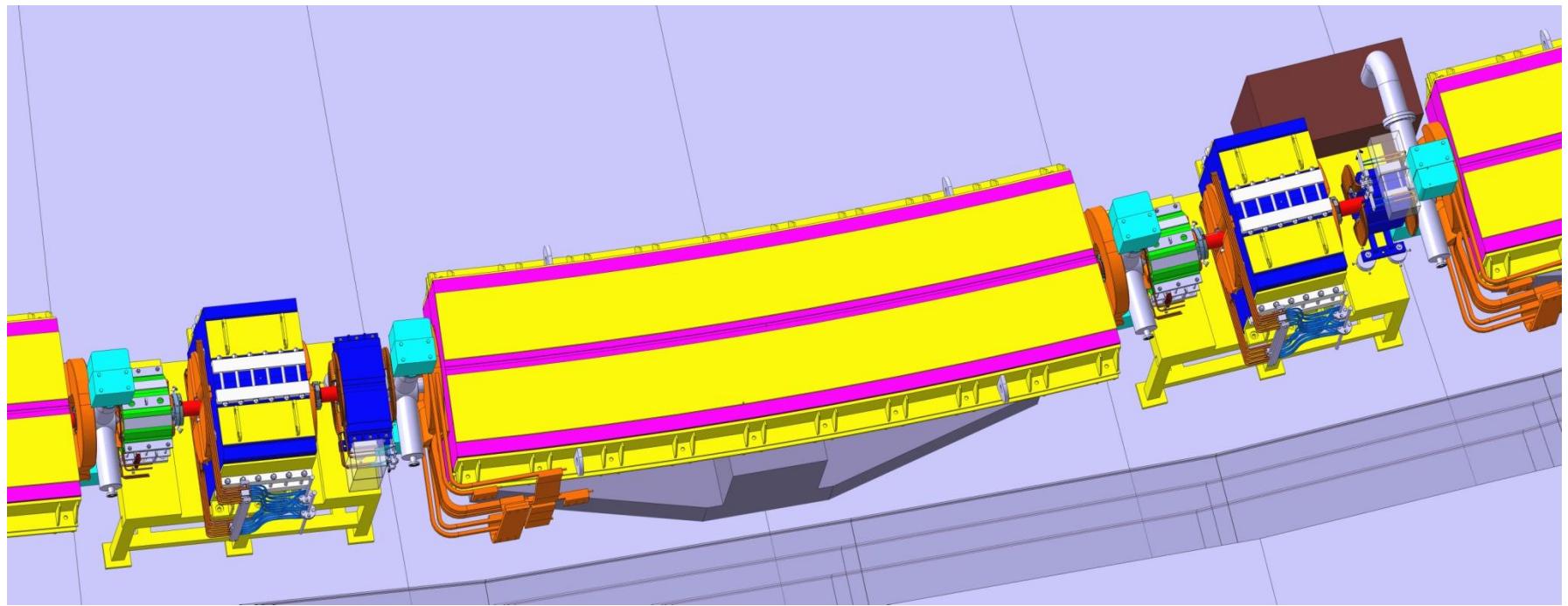


- Circumference 574 m
- Momentum (energy) range 1.5 to 15 GeV/c (0.8-14.1 GeV)
- Injection of (anti-)protons from RESR at 3.8 GeV/c
- Maximum dipole field: 1.7 T
- Dipole field at injection: 0.4 T
- Dipole field ramp: 0.025 T/s
- Acceleration rate 0.2 (GeV/c)/s

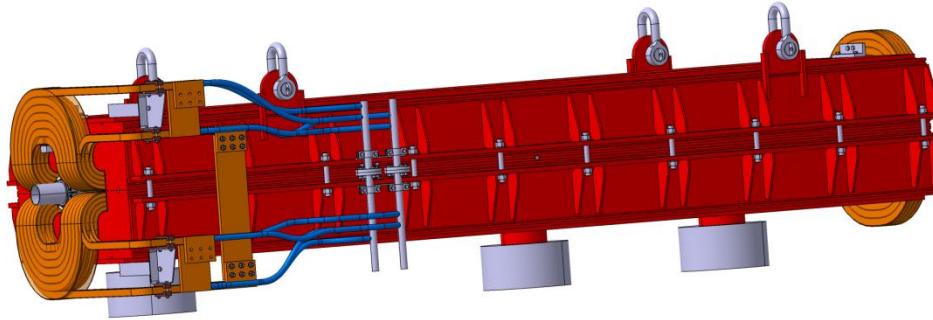
# HESR Arc



# Half FODO Cell



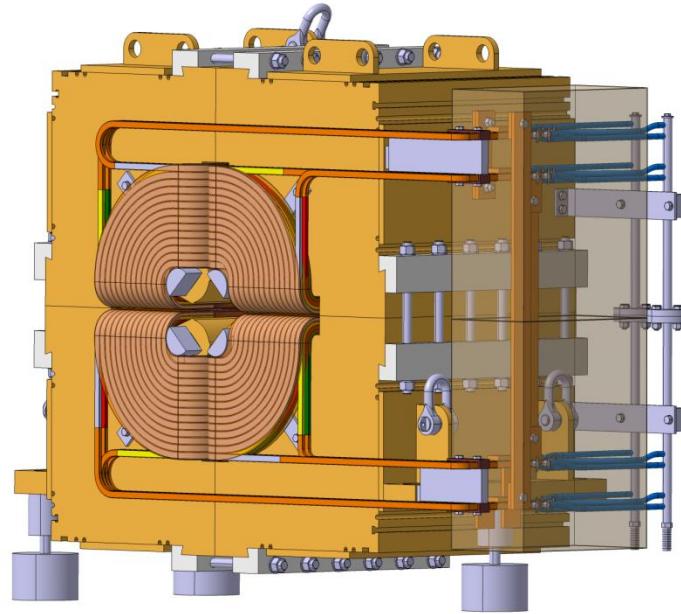
# Dipoles



<b>⑩Number</b>	44
<b>⑩Magnetic length</b>	4.2 m
<b>⑩Iron length (arc)</b>	4.126 m
<b>⑩Deflection angle</b>	8.182°
<b>⑩Max B-field</b>	1.7 T
<b>⑩Min B-field</b>	0.17 T
<b>⑩Aperture</b>	100 mm
<b>⑩Number of turns per coil</b>	24
<b>⑩Current</b>	2922 A
<b>⑩Current density</b>	4.4 A/mm <sup>2</sup>
<b>⑩UDC</b>	36 V
<b>⑩R (dipole)</b>	12.3 mΩ
<b>⑩L (dipole)</b>	40 mH

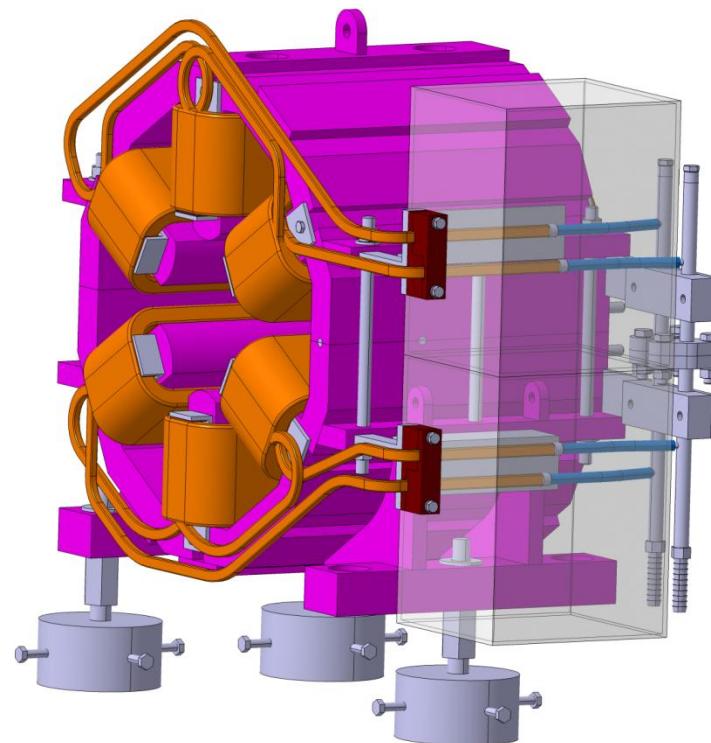
# Quadrupoles

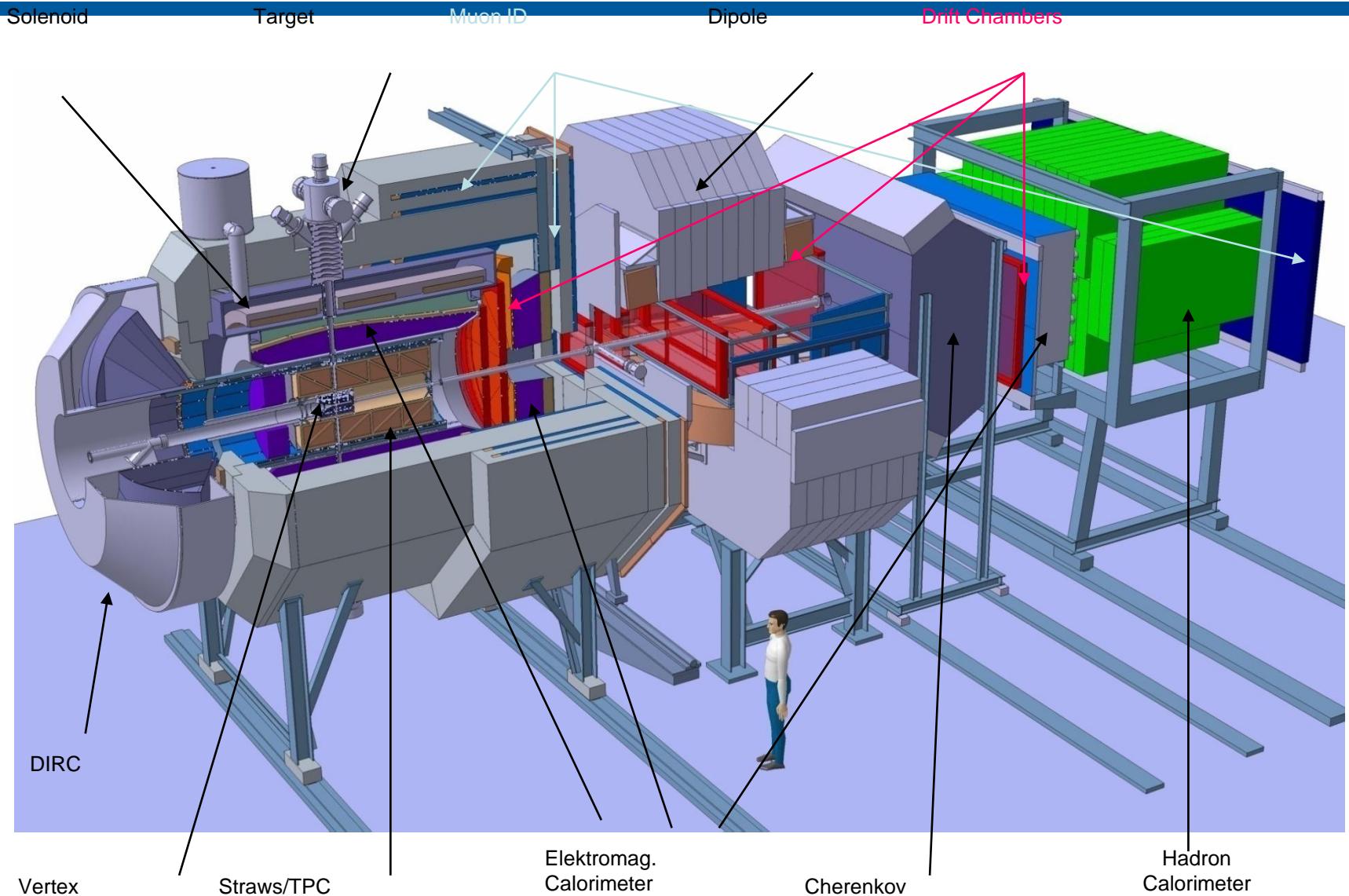
⑩ Number	84
⑩ Magnetic length	0.6 m
⑩ Iron length (arc)	0.58 m
⑩ Max gradient	20 T/m
⑩ Aperture	100 mm
⑩ Number of turns per coil	100
⑩ Current	300 A
⑩ Current density	6.8 A/mm <sup>2</sup>
⑩ UDC	55.3 V
⑩ R (quadrupole)	184 mΩ



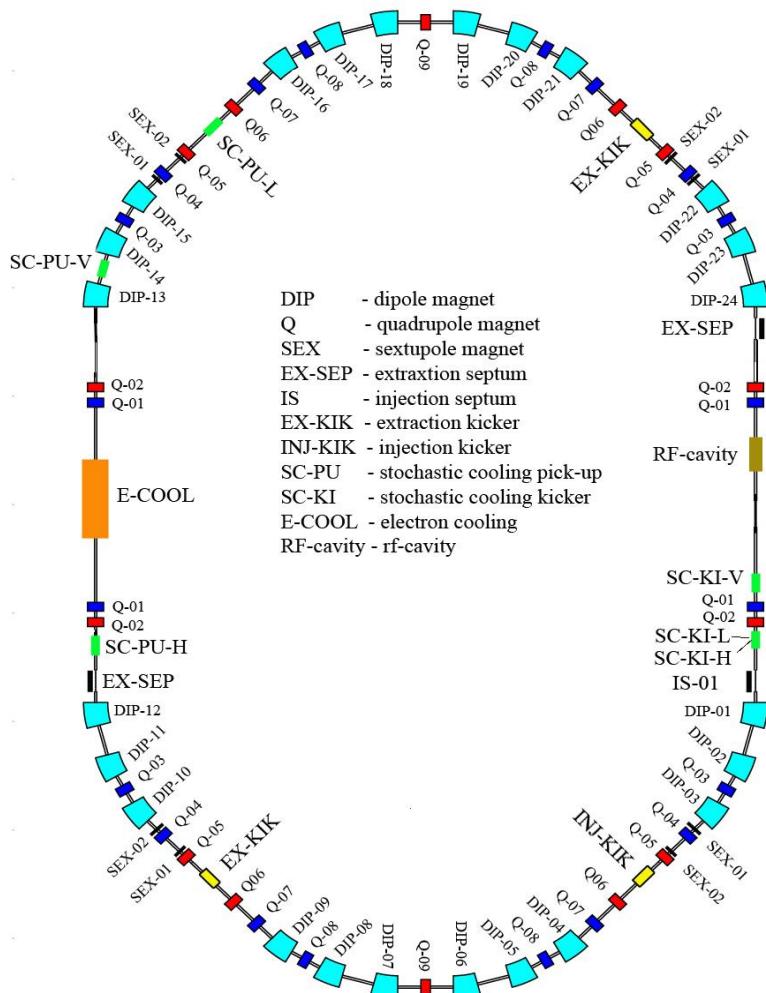
# Setupoles

⑩ Number	52 in arcs
⑩	8 in straights
⑩ Magnetic length	0.3 m
⑩ Max $d^2B/dx^2$	42.5 T/m <sup>2</sup>
⑩ Aperture allow insertion of beam	135 mm (to
⑩ position monitors)	





# RESR The Antiproton Accumulator Ring



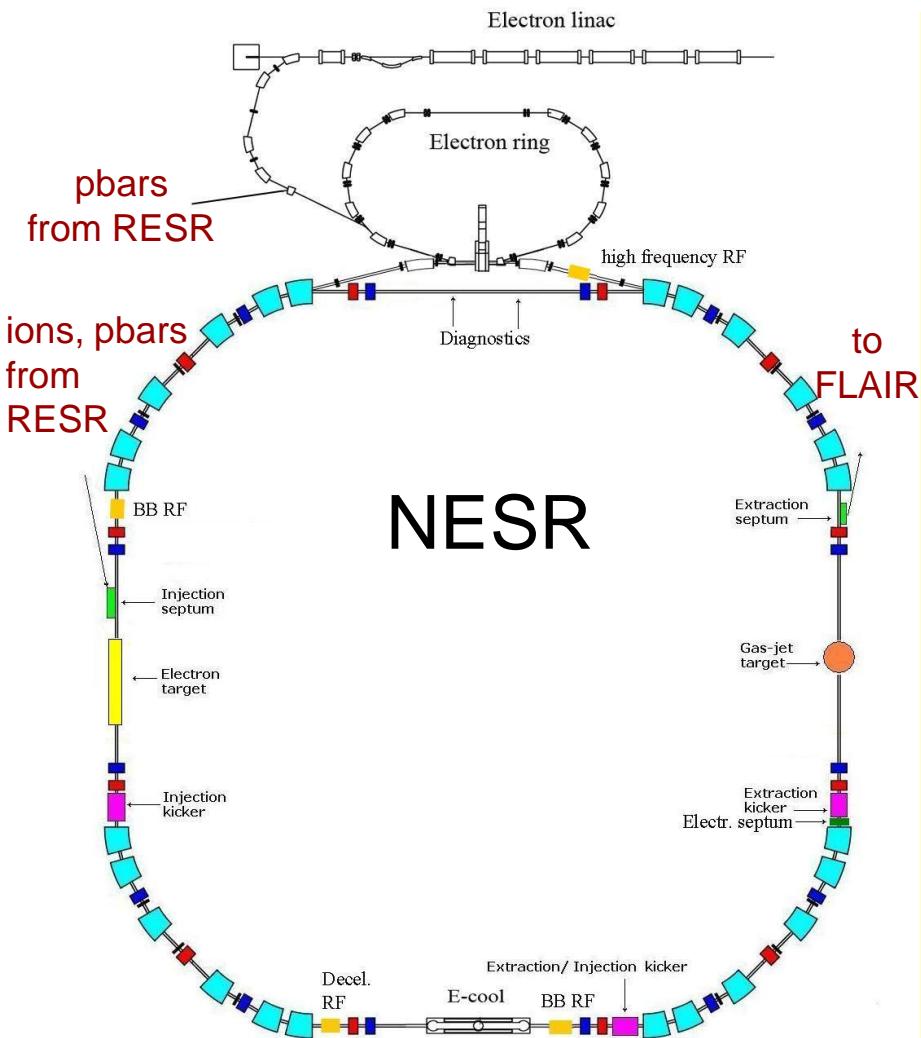
circumference	240 m
magnetic bending power	13 Tm
tunes $Q_x/Q_y$	3.12/4.11
momentum acceptance	$\pm 1.0 \%$
transverse accept. h/v	$25 \times 10^{-6} \text{ m}$
transition energy	3.3-6.4

accumulation of antiprotons  
by a combination of rf and  
stochastic cooling

*max. accumulation rate  $3.5 (7) \times 10^{10}/\text{h}$*   
*max. stack intensity  $\sim 1 \quad 10^{11}$*

*additional mode:*  
*fast deceleration of RIBs (antiprotons)*  
*to a minimum energy of 100 MeV/u*  
*for injection into NESR (ER)*  
*for collider mode experiments*

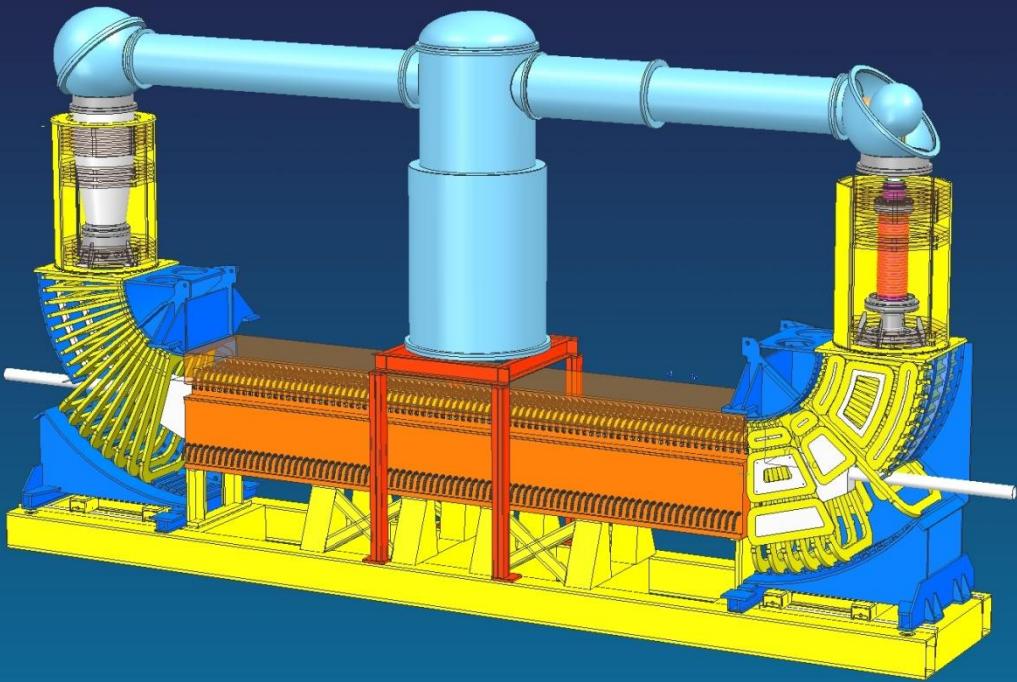
# The New Experimental Storage Ring



- Electron cooling of ions and antiprotons
- Fast deceleration of ions to 4 MeV/u and antiprotons to 30 MeV
- Fast extraction (1 turn)
- Slow (resonance) extraction
- Ultraslow (charge changing) extraction
- Longitudinal accumulation of RIBs
- Electron-Ion collisions (bypass mode)
- Antiproton-ion collisions
- Internal target
- Electron target
- High precision mass measurements

# NESR Electron Cooler

*design by BINP, Novosibirsk*

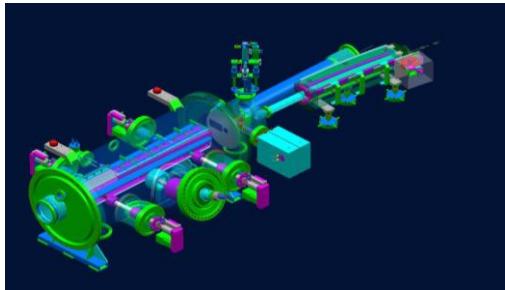


## Electron Cooler Parameters

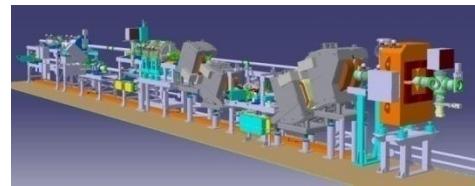
energy	2 - 450 keV
max. current	2 A
beam radius	2.5-14 mm
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	$2 \cdot 10^{-5}$
vacuum	$\leq 10^{-11} \text{ mbar}$

- Issues:
- high voltage up to 500 kV
  - fast ramping, up to 250 kV/s
  - magnetic field quality

# SIS18upgrade Program



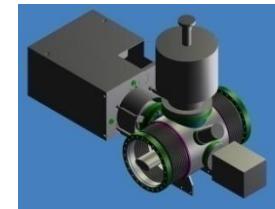
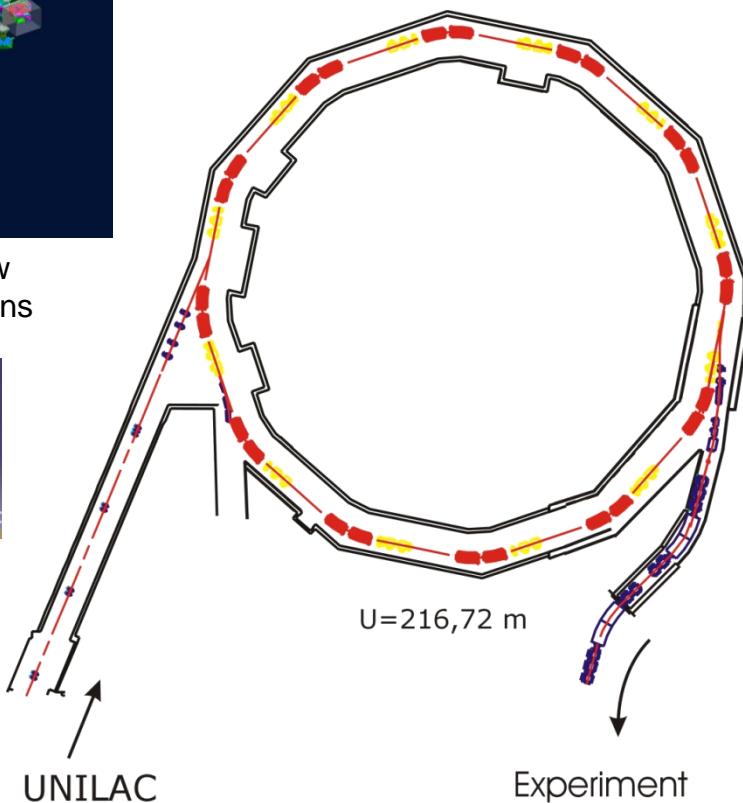
Injection system for low charged state heavy ions



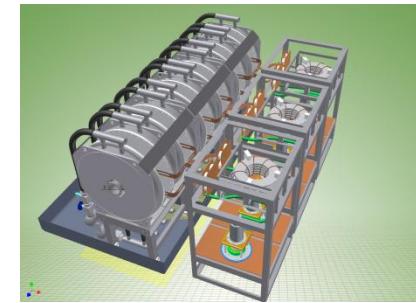
Charge separator for higher intensity and high quality beams



Power grid connection



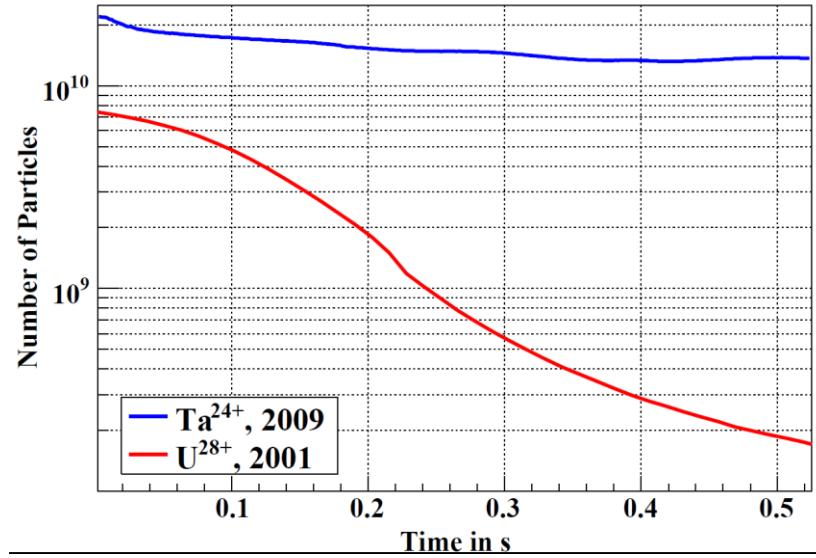
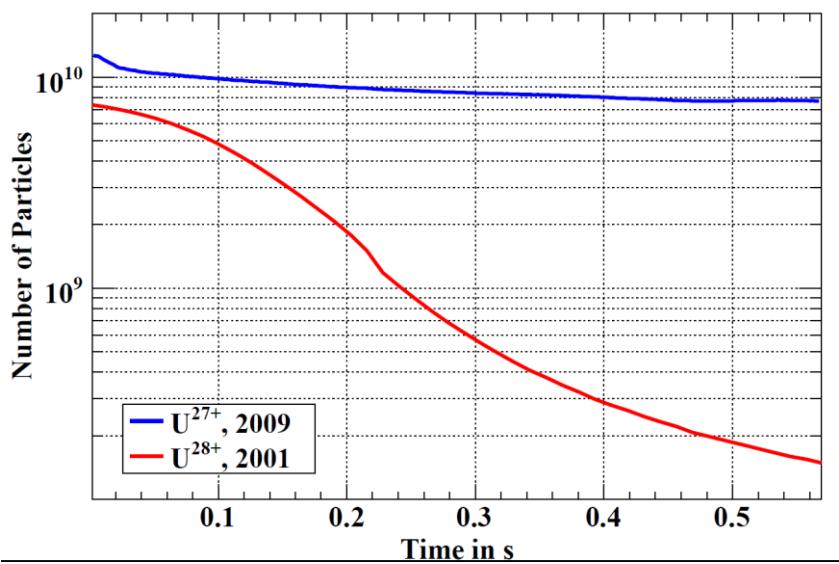
Scrapers and NEG coating for pressure stabilization



$h=2$  acceleration cavity for faster ramping

The SIS18upgrade program: To reach the space charge limit with the heaviest ions.

# Acceleration of Intermediate Charge State Heavy Ions



- Significant progress with  $\text{Ta}^{24+}$  and  $\text{U}^{27+}$  ions due to the upgrade program in comparison with 2001
- Maximum beam energy about 200 MeV/u

# Layout and Design parameters for the Super-FRS

## Projectile:

- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to  $10^{12}$  /s  
(depending on element)
- DC or **pulsed** operation

## Design Parameters:

$$\varepsilon_x = \varepsilon_y = 40 \pi \text{ mm mrad}$$

$$\Phi_x = \pm 40 \text{ mrad}$$

$$\Phi_y = \pm 20 \text{ mrad}$$

$$\Delta P/P = \pm 2.5 \%$$

$$B\beta = 2 - 20 \text{ Tm}$$

$$R_{\text{ion}} = 750 / 1500$$

(first / second stage)

Spot size on target

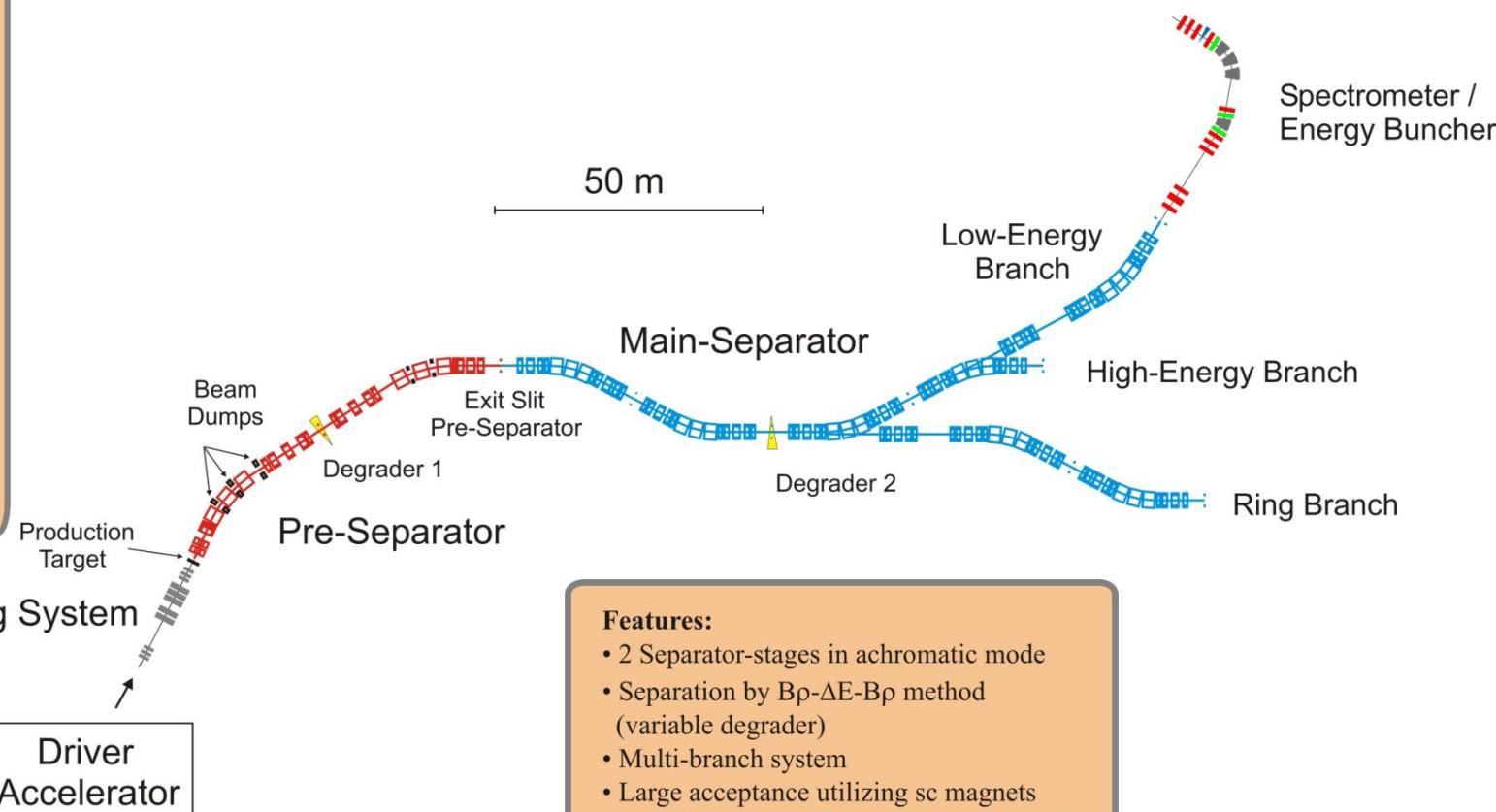
$$\sigma_x = 1.0 \text{ mm}$$

$$\sigma_y = 2.0 \text{ mm}$$

Focusing System

Driver Accelerator

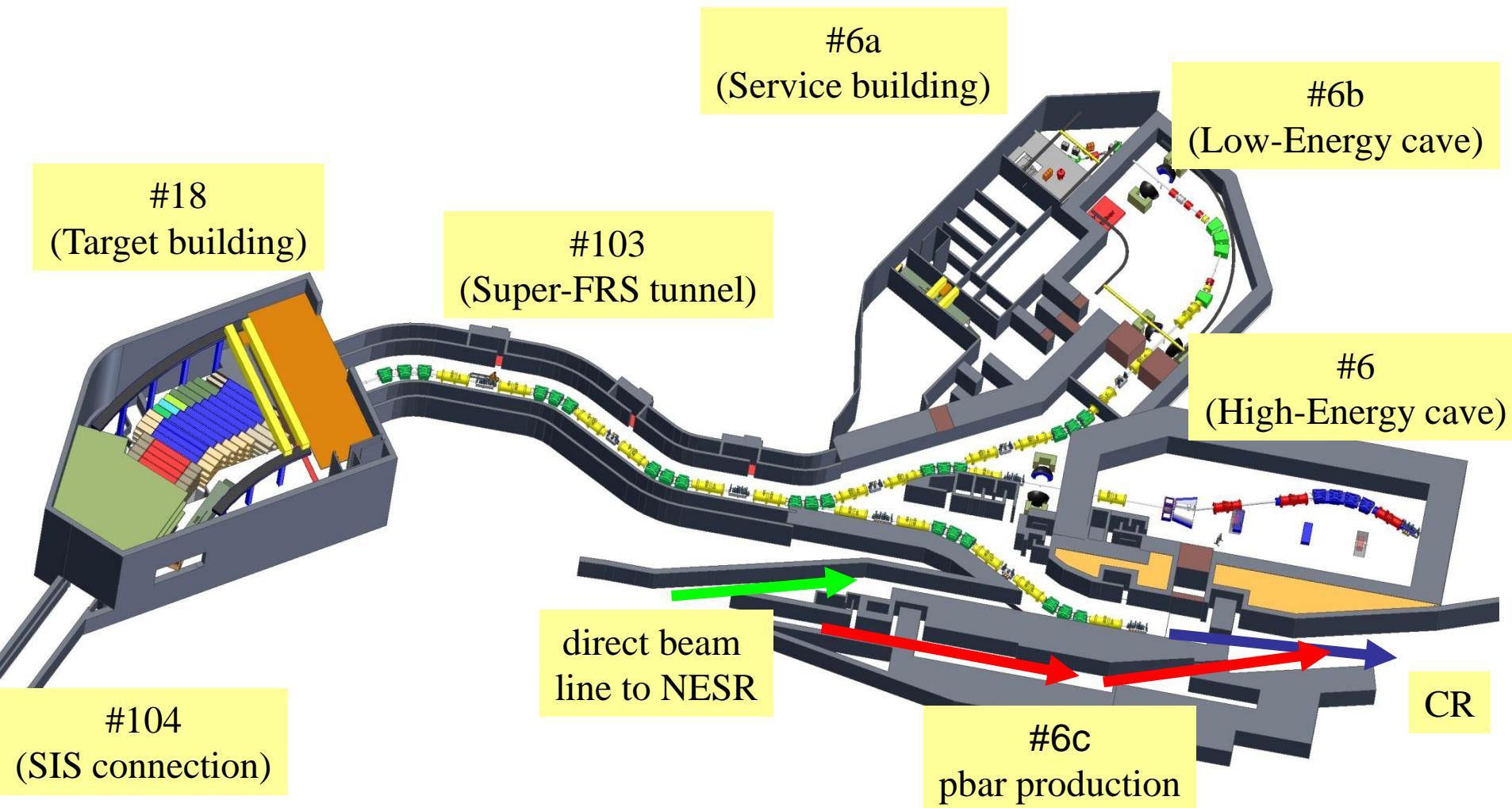
## Goal: Larger Acceptance



## Features:

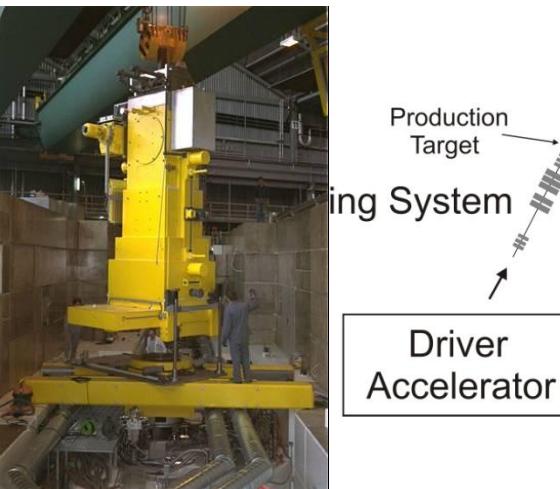
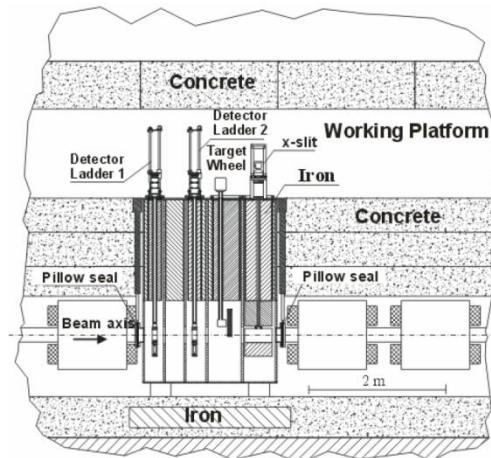
- 2 Separator-stages in achromatic mode
- Separation by  $B\beta - \Delta E - B\beta$  method  
(variable degrader)
- Multi-branch system
- Large acceptance utilizing sc magnets
- Handling concept for high- radiation area

# Super-FRS Buildings

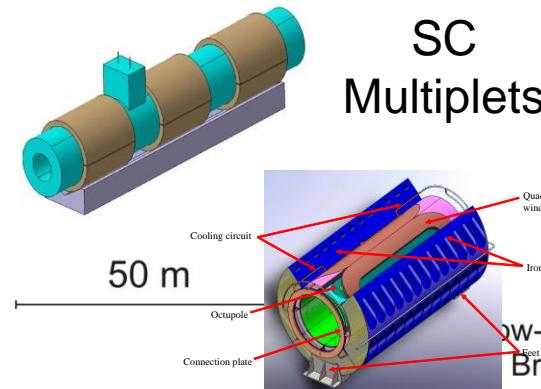


# Technical Challenges

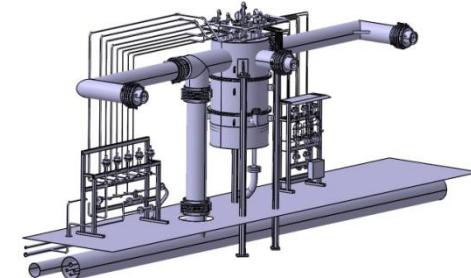
## Remote Handling



## Target & Beam Catcher



## SC Multiplets



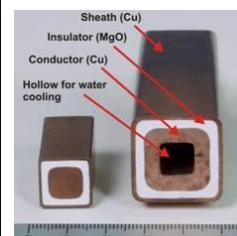
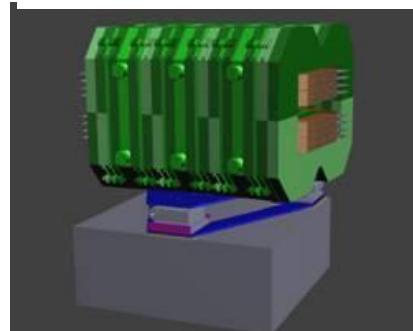
## Cryogenics



## SC Dipoles



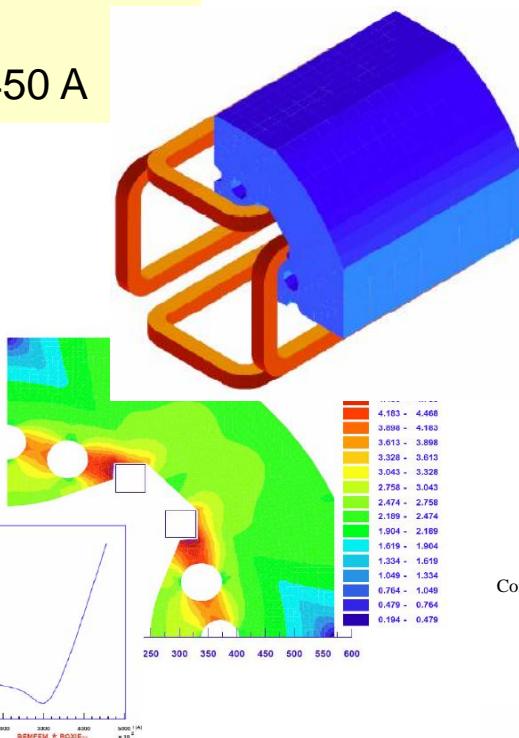
## Radiation Resistant Magnets



# Super Conducting Multiplet Design (Consortium by France/Spain)

## Optimization by CIEMAT/Spain

- superferric type (field shaping)
- less cold iron
- operation current at 450 A



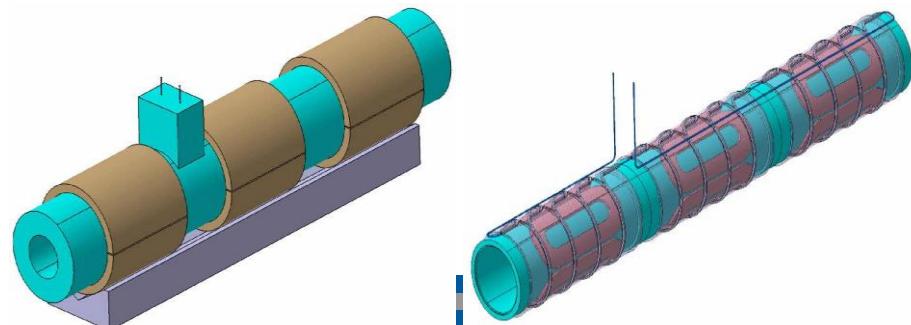
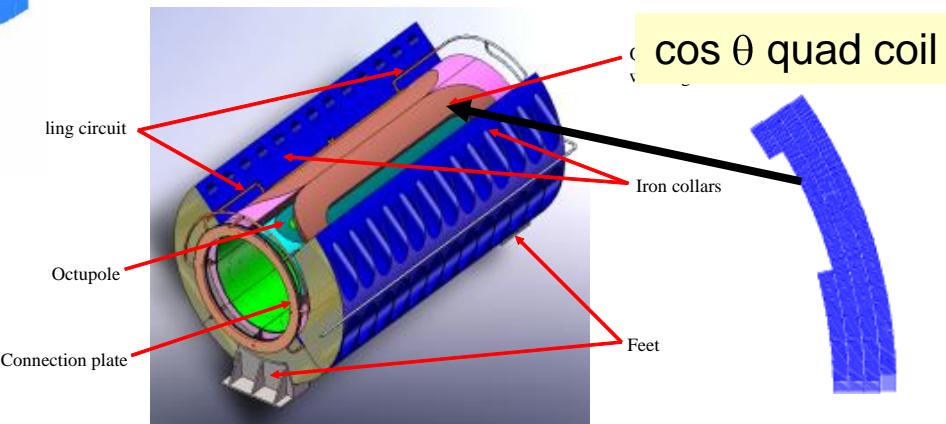
## • New parameters

- Iron mass: 4430 kg
- Coil SC area: 666 mm<sup>2</sup> (Cu/Sc=2.4)
- Inductance: 11.9 H/m
- Stored energy: 1181 kJ/m
- 51.7x53 mm coil, 1.18x1.88 mm wire
- 444 Amps, 1026 turns
- Quality up to 5 T/m (r=190 mm):
  - B6: -1 to 3 units of 10<sup>-4</sup>
  - B10: -2 to 2 units of 10<sup>-4</sup>
  - B14: -1 units of 10<sup>-4</sup>
  - B18: -0.2 units of 10<sup>-4</sup>
- Peak field in coil: 4.85 T
- Max. percentage on load line: 60.9%

- Both collaborators provided a conceptual design report
- Review by MAC
- start of pre-series multiplet

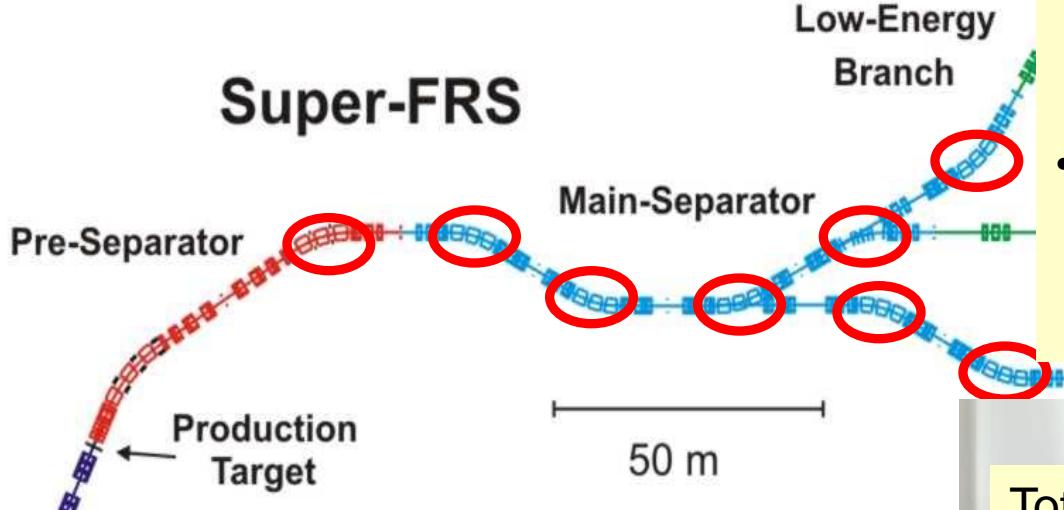
## Alternative proposal by CEA/France

- $\cos \theta$  solution
- no helium vessel, indirect cooling
- high current (~800 A), strong forces
- field quality sensitive to coil placement

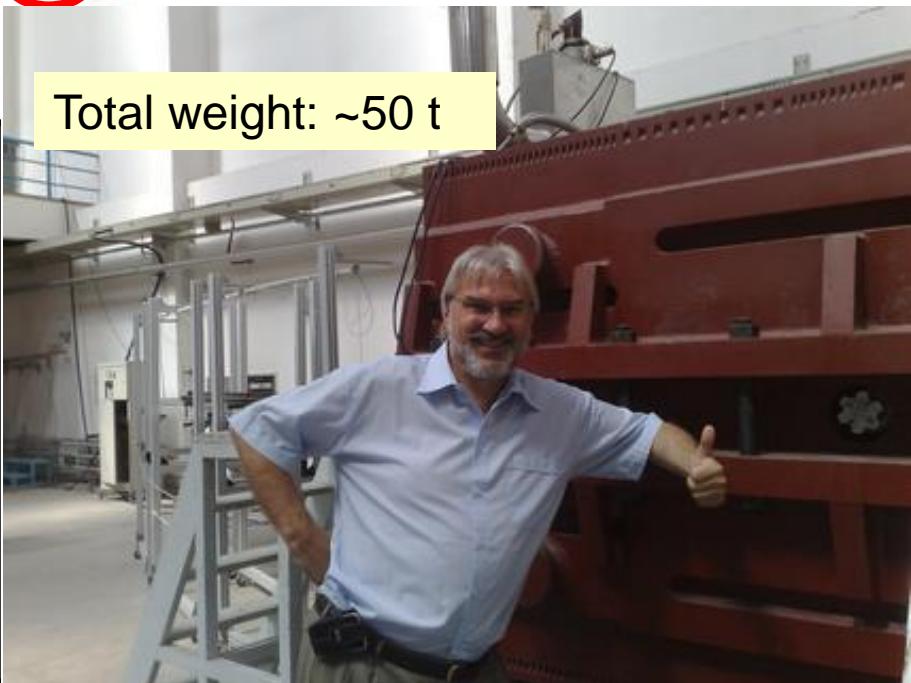


# Superferric Dipoles for the Main Separator

## Super-FRS



- Enerav**
- Prototype fabrication by **FCG**  
**IMP Lanzhou**,  
Inst. of El. Eng. **Beijing**,  
Inst. of Plasma Phys. **Heifei**
  - Prototype status  
Magnet is assembled  
Test under way



Number of main dipoles		<b>21</b>
Dipole field	<b>T</b>	<b>0.15-1.6</b>
Bending angle	<b>Degree</b>	<b>9.75</b>
Curvature radius, R	<b>m</b>	<b>12.5</b>
Effective straight length, $L_{\text{effe.}}$	<b>mm</b>	<b>2127</b>
Good field region	<b>mm</b>	<b><math>\pm 190 \pm 35</math></b>
Pole gap height	<b>mm</b>	<b>170</b>
Integral field quality (relative)		<b><math>\pm 3 \times 10^{-4}</math></b>

# Preparatory Phase R&D by GSI & Partner Institutes since 2001

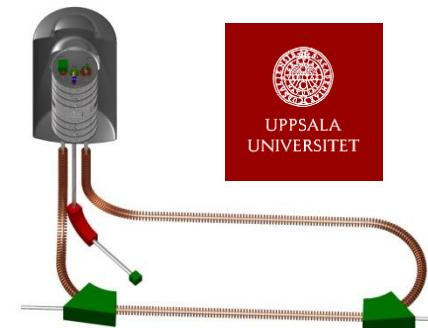


IHEP Protvino

SIS300 magnets



NESR Electron Cooling



CEA / CNRS

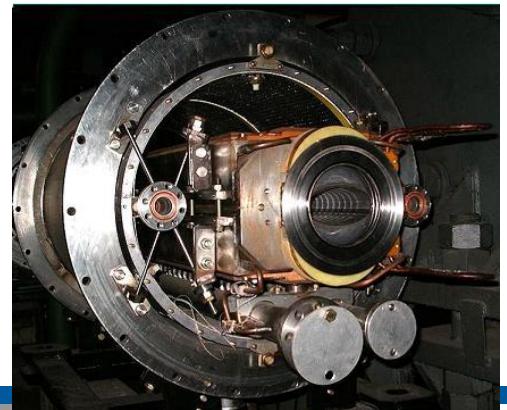
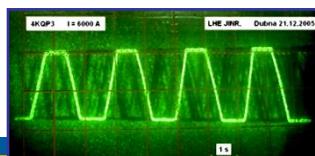
Variable Frequency  
Cavities



BINP Novosibirsk



SIS100 rapidly cycling sc magnets



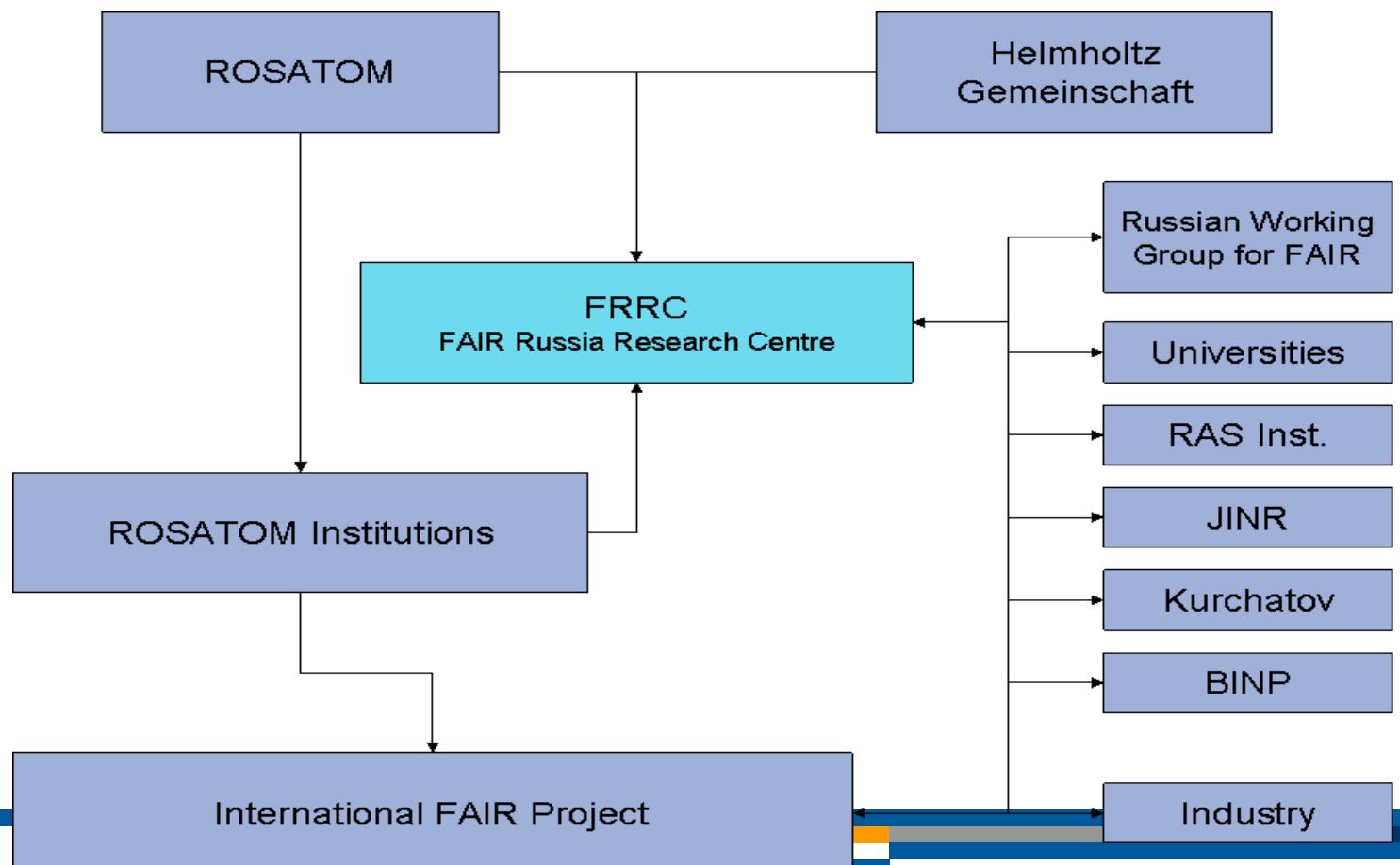
**20 июня 2008**

**открытие Исследовательского Центра  
Росатом - Гельмгольц**



# Исследовательский Центр ФАИР - Россия

1. Координация Российского участия в проекте ФАИР
2. Поддержка аспирантов, молодых ученых, инженеров, специалистов,
3. Инфраструктура для проведения совещаний, семинаров, технических митингов, научно-образовательного процесса,
4. Поддержка развития научных исследований, технологических разработок в университетах, НИИ, в промышленности высоких технологий.



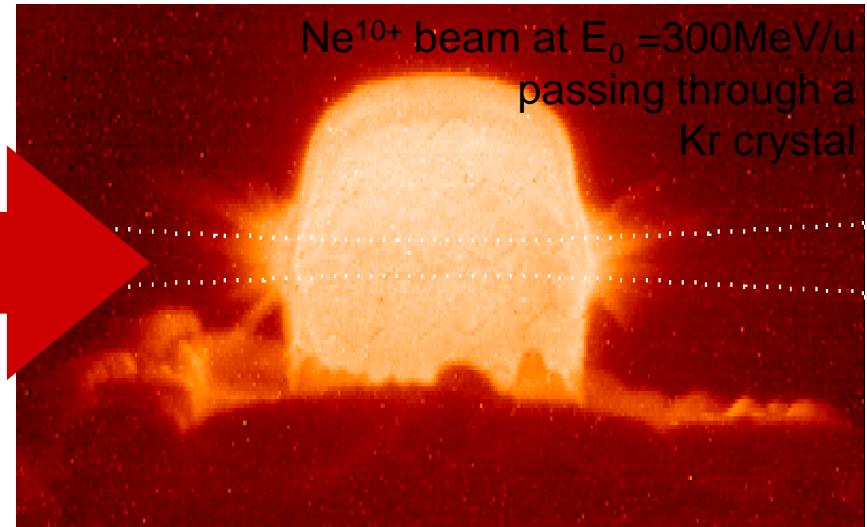
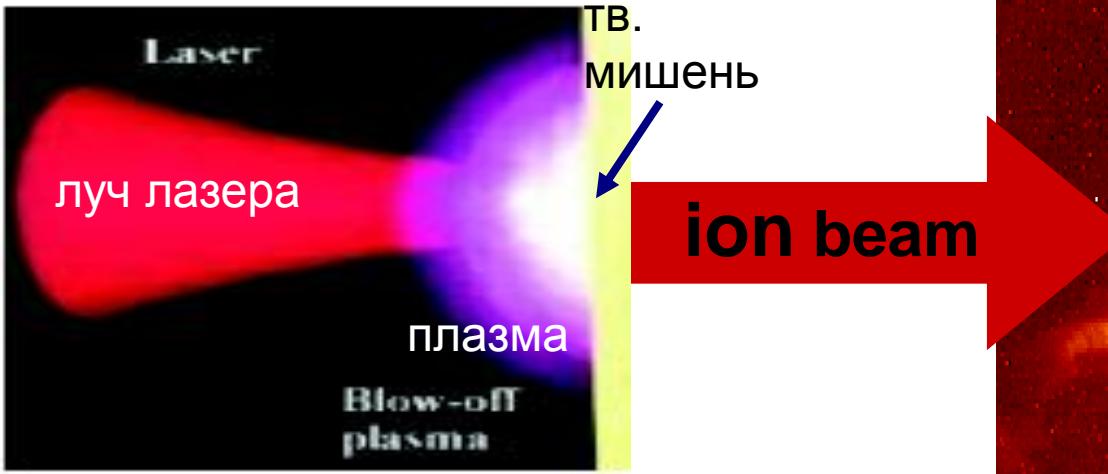
# Participation in FAIR project opens opportunity for :

- Support of local research institutions
- Support and education of local young generation of scientists
- Investments in development of local high-tech industries
- Support in development of novel detector materials and technologies
- Access to forefront accelerator technologies
- Development and implementation of modern IT technologies
- Access to unique variety of beams of heavy ions, antiprotons and radioactive isotopes

# *Thank you for attention !*



# Интенсивные ионные пучки – инструмент для генерации и исследования экстремального состояния вещества в воспроизводимых экспериментальных условиях



## Мощные лазеры

NIF, Omega, Gekko XII, LMG, Искра-5,6, X-FEL....

поверхностное энерговыделение  
малая частота  
малый объем  
большие градиенты T, Ne

короткие времена процессов

## Пучки тяжелых ионов

SIS-18, TBH, SIS-100

объемное энерговыделение  
1 – 0.1 Гц  
большие объемы (N mm<sup>3</sup>)  
однородные условия при высокой  
энтропии и большой плотности

T > 1 – 10 нс  
КПД ускорителей – 25%

Состояние с высокой энтропией без ударного сжатия !